VIDEO BANDWIDTH REDUCTION/COMPRESSION RESEARCH FOR THE ARMY REMOTELY PILOTED VEHICLE SYSTEM

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A simulation and research program was conducted in support of the U.S. Army Remotely Piloted Vehicle Target Acquisition/Designation Aerial Reconnaissance System. The research was directed towards RPV operation in a jamming environment, using video bandwidth reduction/compression techniques. Two simulation studies were conducted to investigate the effects of bandwidth compression on operator target detection and recognition performance and the effects of frame rate reduction on operator sensor slewing performance during the search phase

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of the RPV mission. The results of the two studies provided data to define levels of bits per picture element bandwidth compression and frames per second frame update rate in combination with other selected RPV system and operating conditions.

PREFACE

Contractual support for this research was provided by the U.S. Army Electronic Research and Development Command, DELCS-XX, Fort Monmouth, New Jersey, contract number DAAB07-78-C-2415. Mr. A. Lukosevicius was the Army Program Manager, and Mr. A. Farnochi provided technical support and consulting. The research was conducted by personnel from the Display Systems Laboratory of the Radar Systems Group, Hughes Aircraft Company. Mr. M. L. Hershberger was the Program Manager and Dr. A. K. Agin was the Principal Investigator.

Special acknowledgement is gratefully made for the following contributions to the program: Messrs. R. L. Andrews and J. A. Schrunk for their invaluable work with the RPV simulator equipment and Mr. B. Ulrick for his analog computer programming talent.

A-1

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION 1

INTRODUCTION AND SUMMARY

BACKGROUND

The U.S. Army is currently engaged in a program to design, develop, and test a remotely piloted vehicle target acquisition/designation aerial reconaissance system with Lockheed Missiles and Space Company of Sunnyvale, California as the prime contractor. The Remotely Piloted Vehicle (RPV) system will provide unmanned day-night, adverse weather reconnaissance, surveillance, target acquisition, adjustment of field artillery fire, target designation, and damage assessment support to combat elements of U.S. Army divisions.

A RPV ground control station (GCS) will be the operational control center of the RPV system. The GCS will provide the interface among the air vehicle, control station personnel, and various subsystems. It will also serve as the command post for the RPV mission commander and as the communications point for the receipt of mission assignments from supported headquarters, reporting of acquired data to the supported unit, and the transmission of target information to weapon fire direction systems. The GCS will house three Army personnel, three control-display consoles, and various other equipments. The three Army personnel are the mission commander, an air vehicle controller, and a mission payload operator.

The mission payload operator (MPO) is responsible for target search, detection, recognition, designation, tracking, and artillery adjustment functions necessary to accomplish the target acquisition/designation aerial reconnaissance mission. The primary source of information the MPO will use to accomplish his functions is TV video. The TV video will be data linked from the air vehicle to the ground control station over a wide band data link.

The RPV system is being designed to operate in hostile environments in which noise jammers are expected to be present. Video noise jamming reduces the video signal-to-noise ratio which degrades the quality of the video data and degrades the operator's task performance. Because jamming effectiveness is directly related to video bandwidth, the primary countermeasure against jamming is to reduce video bandwidth. Video bandwidth reduction can be accomplished by simple bandwidth reduction or by bandwidth compression. Simple bandwidth reduction includes such techniques as frame rate reduction, resolution reduction, and video image truncation. Bandwidth compression utilizes image transform techniques to reduce the number of transmitted bits per picture element. While video bandwidth reduction/compression is an effective countermeasure against jamming, the process of reducing and/or compressing the video bandwidth can itself degrade video image quality and can make operator sensor control time consuming and inaccurate. The challenge is to achieve the maximum amount of video bandwidth reduction/compression and at the same time prevent or minimize degradation of operator task performance.

SCOPE AND PURPOSE

The research reported herein addressed two areas of video bandwidth reduction/compression for Army RPV system design and operation: 1) the impact of video bandwidth compression on operator tactical target detection and recognition and 2) the impact of frame rate reduction on operator sensor slewing control. These two areas were addressed using man-in-the-loop simulation techniques.

A RCA developed cosine/DPCM video image transform system interfaced to a Hughes RPV simulation facility was used to conduct the bandwidth compression research. Bandwidth compression levels of 0.4, 0.8, 1.6, 3.2, and 6.0 bits per picture element were investigated in combination with:

- 5-, 10-, and 40-kilometer atmospheric visibilities,
- armored personnel carrier, tank, 170-mm self-propelled gun, 2-1/2 ton truck, and jeep target types,
- single and groups of 10 targets (target numerosity),
- broadside and 45-degree forward quartering target aspects, and
- low, medium, and high rated levels of target scene background complexity.

The primary measure of operator task performance was the number of TV lines across the targets' height when detection and recognition occurred.

The sensor slewing control research was accomplished using the Hughes RPV simulation facility specially modified to satisfy the operator task, study parameter, performance measure, and methodological requirements of the simulation study. Video frame update rates of 0.12, 0.47, 1.88, and 7.50 frames per second were investigated in combination with:

- continuous rate, image motion compensation, and bang-bang control modes, and
- 5-, 10-, and 15-degree diagonal sensor fields of view.

These three RPV system design parameters were investigated for two operator sensor control tasks: 1) coarse sensor slewing which required the operators to slew the sensor and search the displayed field of view (target search) and 2) slew the sensor to place the target near the center of the displayed field of view (target line-up).

Time and probability of successful task accomplishment for both the target search and target line-up tasks were the primary performance measures. The operators' evaluation of the difficulty of using the four frame rates and three control modes was also measured using the modified Cooper-Harper rating scale.

RESULTS AND RECOMMENDATIONS

Both bandwidth compression and target numerosity had large and highly statistically reliable effects on operator target detection and recognition performance. These two parameters were also found to interact with each other. Figures 1 and 2 show this interaction effect for target detection and target recognition performance, respectively. Figure 1 shows that bandwidth compression had no affect on the operators' ability to detect groups of 10 targets. Single targets, on the other hand, were much more difficult to detect, and the image quality degradation caused by the higher bandwidth compression levels made the operators' task more difficult.

The interaction between bandwidth compression and target numerosity for target recognition, shown in Figure 2, also indicates groups of 10 targets are less susceptible to bandwidth compression performance degradation than single targets.

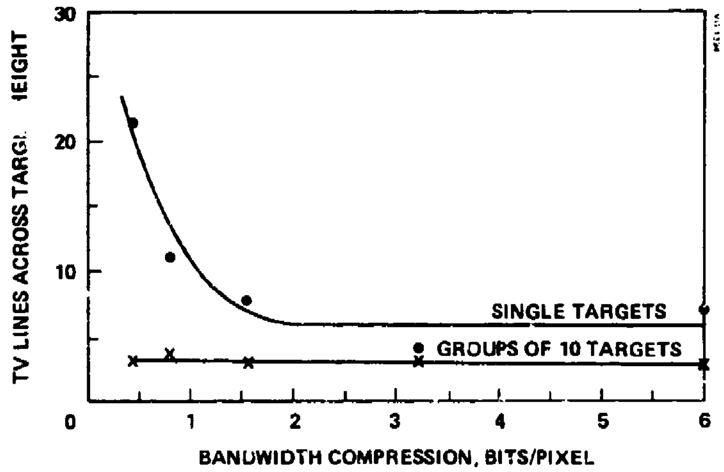


Figure 1. Interaction Between Bandwidth Compression and Target Numerosity For Target Detection Performance

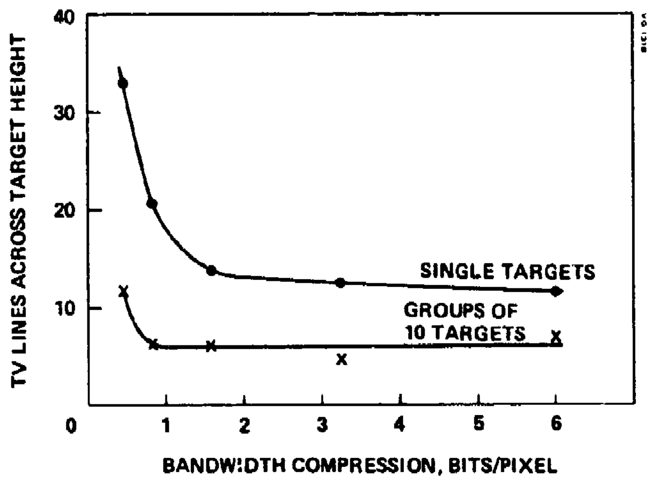


Figure 2. Interaction Between Bandwidth Compression And Targec Numerosity For Target Recognition Performance

These results indicate that single targets place the driving requirement on the level of bandwidth compression that can be achieved without major degradation of operator target detection and recognition performance. This level of compression is in the region of 2 bits per picture element.

Video frame rate, sensor control mode, and sensor field of view all had significant affects on the operators' ability to perform sensor slewing. Figure 3 shows the effects of frame rate and control mode on operator target search and target line-up task time performance.

For the RPV mission payload operator to perform manual sensor slewing for large area target search, the video frame rate should be on the order of 2 frames per second or greater. The choice of a particular control mode will have little affect on the operator's large area sensor slewing performance, given the control mode selected is reasonably well designed. Large fields of view are advantageous for large area sensor slewing.

Video frame rate and sensor control mode both determine the operator's ability to slew the sensor to position the target near the center of the sensor field of view. At a frame rate of 7.5 frames per second, any reasonably

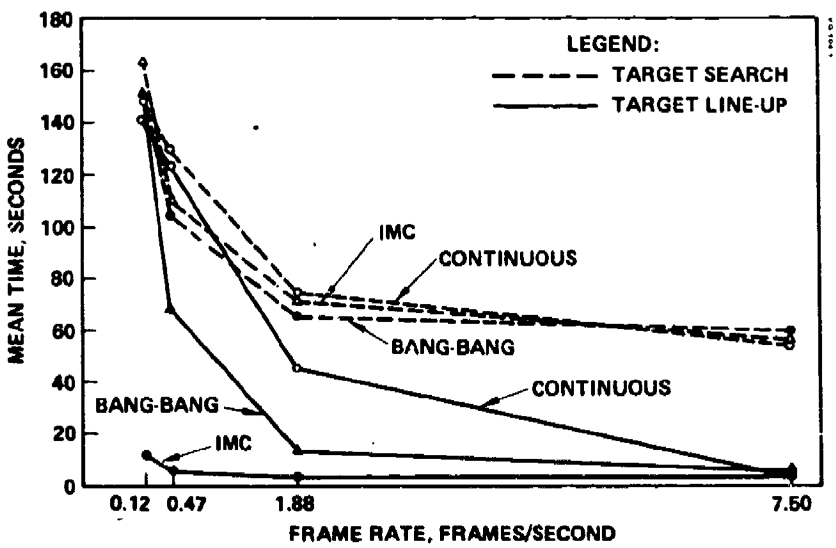


Figure 3. Interaction Between Video Frame Rate And Sensor Control Mode For Operator Task Time

well designed control mode will result in a high level of operator performance. With an image motion compensation type of control mode, frame rates as low as 0.12 frame per second will result in acceptable performance. With a bang-bang type of control mode, frame rates as low as 2 frames per second will result in acceptable operator performance. With a conventional rate control system, a frame rate of 7.5 frames per second, or based on earlier research,[1,2] a frame rate of 3.75 frames per second may be necessary to achieve acceptable levels of operator performance. Field of view is not an important determiner of an operator's ability to slew the sensor to get the target near the center of the field of view, except when the frame rate-control mode combination results in a difficult control task and the operator allows the target to move out of the sensor field of view.

The findings of this research indicate a 2 bits per picture element (3:1 reduction) bandwidth compression is realizable without any appreciable loss of operator target detection and recognition performance. A 15:1 bandwidth reduction (compared to a 30 frames per second frame rate) can be achieved using a 1.88 frames per second frame rate during the manual sensor slewing target search process. Once the target is found, a 256:1 bandwidth reduction is attainable if an image motion compensation type of control system is used to slew the sensor for target line-up.

[1] Hershberger, M. L. Operator Performance Evaluation of Mini-RPV Video Image Bandwidth Reduction/Compression Techniques, Hughes Aircraft Company, Culver City, California, Hughes Report No. TP76-125, Contract No. N66001-75-C-0228, June 1976.

[2] Hershberger, M. L. and Vanderkolk, R. J. Video Image Bandwidth Reduction/Compression for Remotely Piloted Vehicles, Hughes Aircraft Company, Hughes Report No. P76-243R, Contract No. F33657-75-C-0532, October 1976.

SECTION 2

TACTICAL TARGET DETECTION AND RECOGNITION WITH BANDWIDTH COMPRESSION

INTRODUCTION

The United States Army's remotely piloted vehicle (RPV) system will use a modular integrated communications and navigation system (MICNS) that includes a cosine/DPCM transform unit to achieve part of its video anti-jam capability. Several competing transform systems have been developed and tested during the past few years, and the Harris Corporation cosine/DPCM was selected for the Army RPV system. All of these developmental systems provided the capability for variation of compression level (bits per picture element), because the appropriate level of compression to achieve desired levels of operator task performance had not been determined.

Most reported operator target acquisition performance research with bandwidth compression systems has addressed RPV missions against large prebriefed location known targets or has used qualitative techniques to assess the effects of bandwidth compression on picture quality. The single known study that investigated operator tactical target recognition performance with bandwidth compression for Army RPV missions used a prototype brassboard 100- by 100-element resolution cosine/DPCM system developed by the Naval Ocean Systems Center. The results of this study, shown in Figure 4, were limited due to the narrow field of view that could be used which was necessitated by the limited resolution. Hence, only target recognition could be investigated, and the target background clutter was unrealistically low. The study reported herein was performed to extend the earlier Navy work to include both target detection and target recognition and the use of realistic target background characteristics.

The portion of the RPV system which was simulated in this study was the video link from the airborne vehicle to the operator's display. The simulation utilized a cosine/DPCM transform system developed by RCA for the Army RPV system. This system has 256- by 262-element resolution. The input video information, which simulated an air-to-ground view from an RPV television

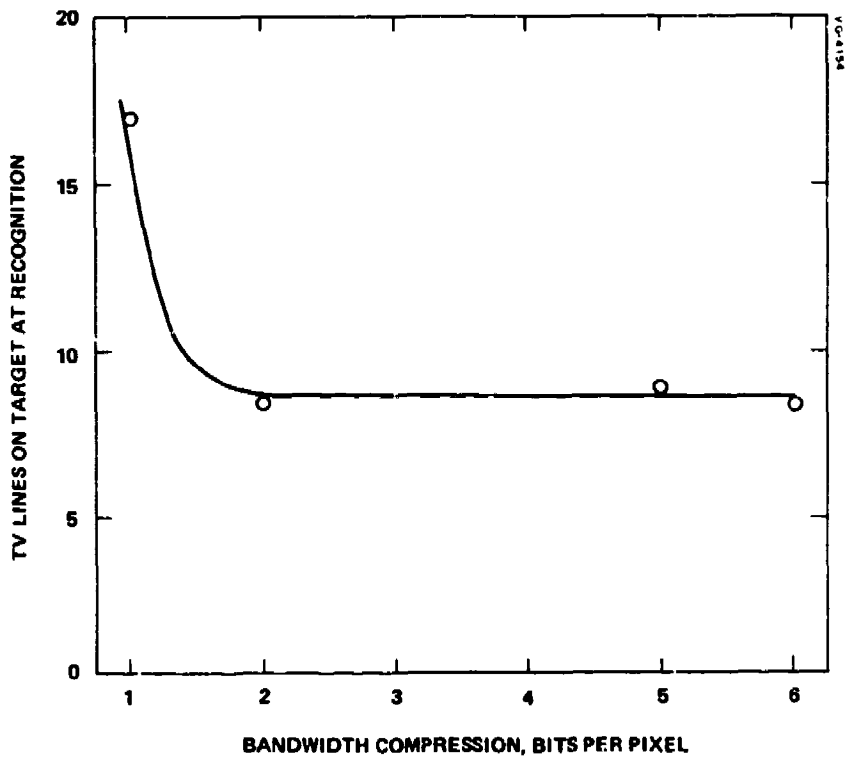


Figure 4. Effects Of Cosine/DPCM Bandwidth Compression On Operator Target Recognition Performance.

sensor, was oblique photographic imagery. The task was a sequential "zoom" task in which increasingly greater magnifications of the target and terrain were shown to the operator in discrete steps. The steps in the series which corresponded to the first correct detection response and the first correct recognition response were the primary performance measures used. The outcome of the research was a set of estimates of operator performance in the RPV system under conditions of bandwidth compression from an airborne unit to a ground station. The results were expressed in terms of TV lines across target height (minimum dimension). This format allowed comparisons to be made with the classical Johnson (NVL) line criteria which are commonly used to define system resolution requirements[3].

[3]Johnson, J. Analyses of Image Forming Systems, In Image Intensifier Symposium, Fort Belvoir, Virginia, October 6 and 7, 1958. (AD220160).

RESEARCH METHODOLOGY

Study Parameters

The primary system parameter of interest in this study was bandwidth compression. Six other variables that determine realistic operating conditions for the RPV system were also investigated. These parameters were atmospheric attenuation, global background (terrain) complexity, target numerosity, target type, target aspect angle, local background complexity, and terrain coverage.

Bandwidth Compression

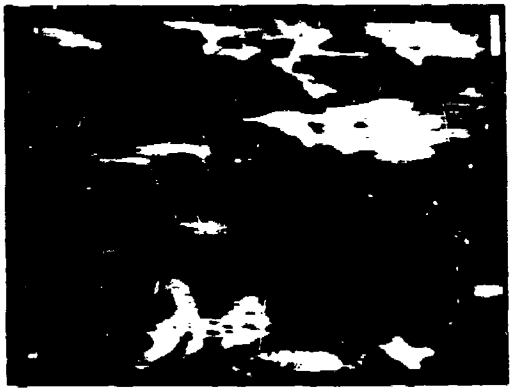
The RCA bandwidth compression unit, hereafter referred to as the ICNS, had a maximum data rate of 3.02 megabits per second based on 256- by 262-element resolution (vertical by horizontal), 6 bits per picture element gray shade encoding, and 7.5 frames per second frame rate. The unit provided the means for discrete selection of five video compression levels as shown in Table 1. An example target scene at the five compression levels for two of the zoom steps is shown in Figures 5 and 6.

TABLE 1. BANDWIDTH COMPRESSION LEVELS

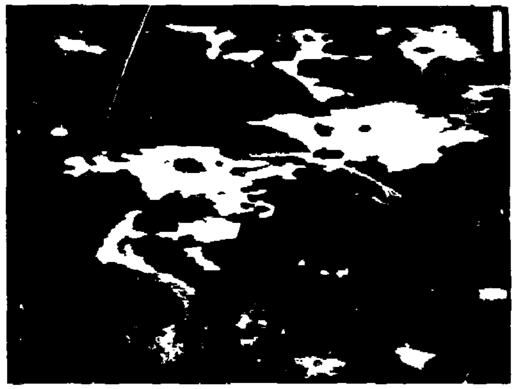
Data Rate, Megabits Per Second	Bits Per Picture Element	Compression Ratio
3.02	6.0	1:1
1.60	3.2	1.875:1
0.80	1.6	3.75:1
0.40	0.8	7.5:1
0.20	0.4	15:1

Atmospheric Attenuation

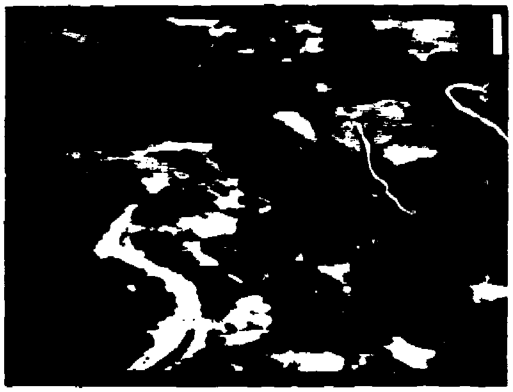
Atmospheric attenuation reduces image contrast, and reduced contrast is known to degrade operator target detection and recognition performance. Atmospheric attenuation was selected as a study parameter because of the unknown relationship between it and bandwidth compression.



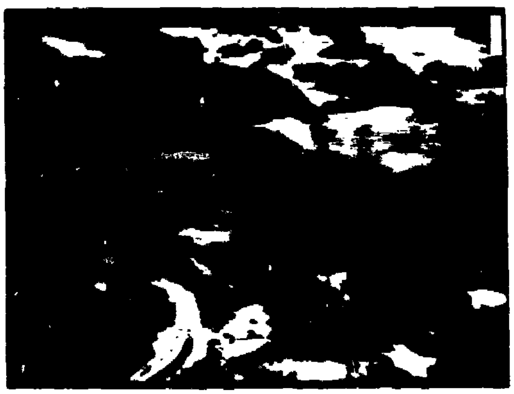
a. 0.4 BIT/PIXEL



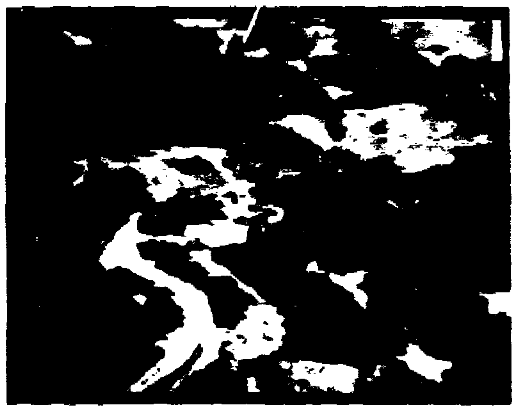
b. 0.8 BIT/PIXEL



c. 1.6 BITS/PIXEL

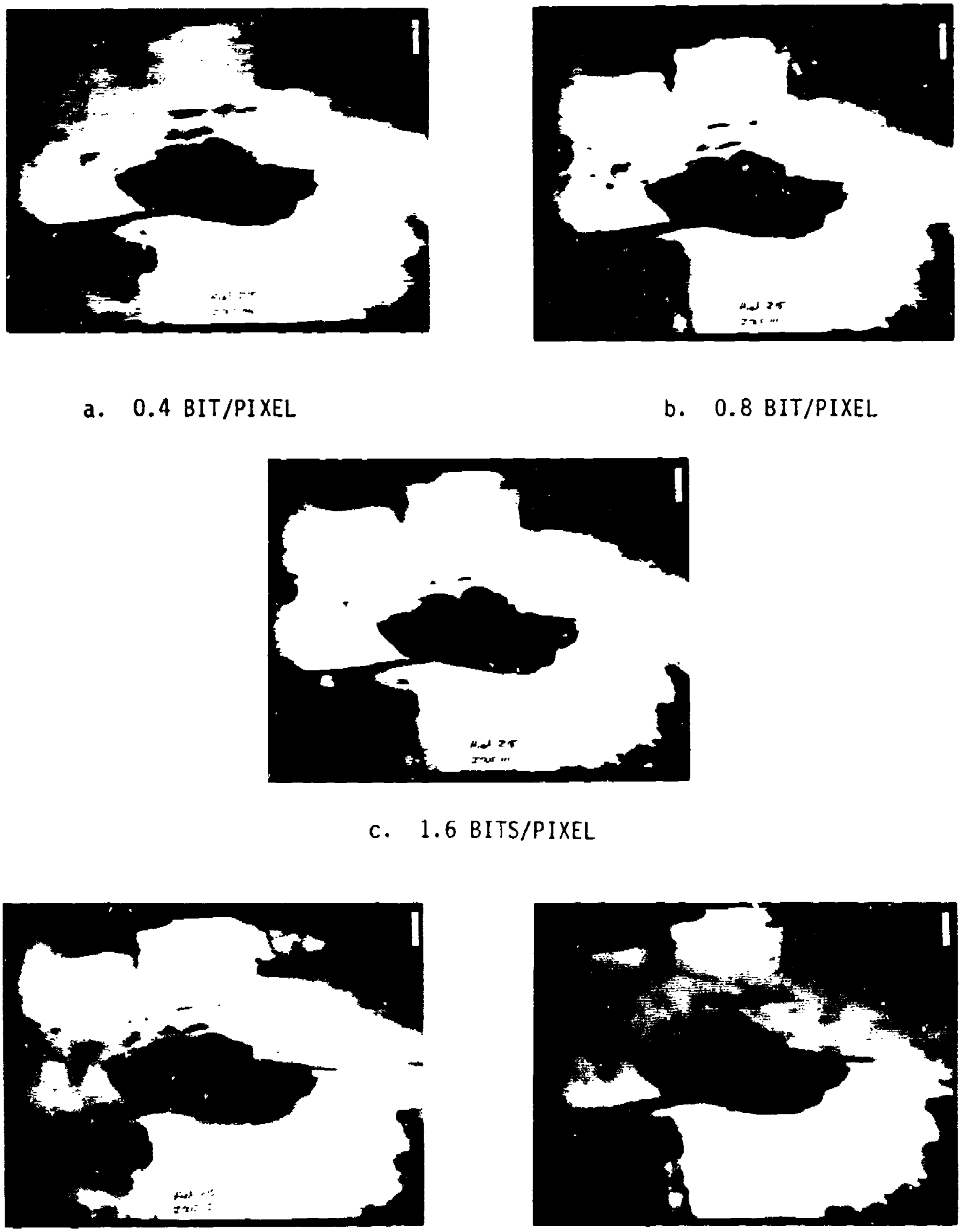


d. 3.2 BITS/PIXEL



e. 6.0 BITS/PIXEL

Figure 5. Example Target Scene At The Five Bandwidth Compression Levels with 3 TV Lines across Targets



a. 0.4 BIT/PIXEL

b. 0.8 BIT/PIXEL

c. 1.6 BITS/PIXEL

d. 3.2 BITS/PIXEL

e. 6.0 BITS/PIXEL

Figure 6. Example Target Scene At The Five Bandwidth Compression Levels With 47 TV Lines Across Targets

Atmospheric attenuation is a result of particles in the air (primarily water) which scatter, or diffract the light. The net effect is reduced target-to-background contrast. Atmospheric attenuation has been approximated successfully by mathematical models[4], and the basic attenuation effect is a function of range to the target and atmospheric visibility. The amount of contrast attenuation is computed with the following equation:

$$C_a = C_o \, e^{(-3.91\, R/V)} ,$$

where C_a is the target to background contrast under atmospheric attenuation

C_o is the inherent target to background contrast; (-3.91) is an empirically derived constant

R is sensor to target range

V is the visibility rating, based on maximum range at which a standard target may be detected.

In this study, three levels of atmospheric attenuation were employed. Based on a fixed nominal range to target of 2 km; visibilities of 40, 10, and 5 km (extremely clear, moderate, hazy); and the inherent target to background contrasts for all targets set at 0.85, the resulting contrast values were fixed at 0.70, 0.40 and 0.18. The contrast in all cases was defined as:

$$\frac{L_{max} - L_{min}}{L_{max}},$$

where L_{min} = minimum (target) luminance

L_{max} = maximum (background) luminance.

Target Parameters

The three target variables in the study were target numerosity, target type, and target aspect angle. Target numerosity was the number of

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[4]Stathacopoulos, G. F., Gilmour, J. D. and Rohringer, G. Review of Mathematical Models of Air-to-Ground Target Acquisition, Naval Weapons Center, China Lake, California, NWC TP5840, January 1976.

vehicles present in an image. There was either a single target or a group of 10 targets. The multiple target groups were parked vehicles in relatively compact configurations with irregular outlines; no linear convoys were used. Target type was represented by five tactical vehicle types: armored personnel carriers (APCs), tanks, 170-mm self-propelled guns (SP-guns), 2 1/2-ton trucks, and jeeps. The aspect angles of targets were either full broadside or 45-degree forward quartering aspect.

Background Variables

There were two variables that were based on terrain and clutter objects visible in the background imagery. Global background complexity was based on ratings by Marine photographic interpreters from El Toro Marine Air Station. The imagery was organized into low, medium, and high levels of rated complexity. The local background complexity was also based on marine photographic interpreter's ratings. The local measure was a rating of the complexity of the background in the immediate target area (3-degree diameter area).

Terrain Coverage

The characteristics of a zoom task normally cause the background to change with each magnification step, because the apparent range or field of view decreases. To obtain information on the influence of terrain coverage on operator performance, both variable and fixed terrain coverage were investigated. In the variable terrain coverage part of the study, horizontal coverage ranged from 870 feet to 58 feet through the 15:1 zoom range. In the fixed coverage part of the study, horizontal terrain coverage remained constant at 58 feet throughout the 15:1 zoom range. The background variables were omitted from the fixed coverage part of the study, because the 58-foot coverage was too small to include much in the way of terrain features. For the same reason, only single targets were used in the fixed coverage study.

Simulation Implementation

The simulation that was developed for this study consisted of three components: hardware, offline software, and video imagery. Bandwidth compression, atmospheric attenuation, and zoom control (magnification level), which determined the number of TV lines across the target, were all controlled through hardware components. Target and background variables were controlled through photographic techniques in the oblique aerial photographic imagery. The operators' task, response measurement, and sequencing of experimental procedures were defined through offline software.

Hardware Simulation

The hardware simulation was a modification of the Hughes RPV Simulator shown in Figure 7. The components were interfaced in an open-loop linear sequence as depicted in Figure 8. All images originated with photographic film mounted in an experimenter-controlled servo platform that could be moved in x and y translation, and z-axis roll. Roll was fixed so that all images were in the correct real-world orientation for the viewer, and the x and y (horizontal and vertical) movement of the image was controlled by the experimenter from a set of potentiometers. The illumination of the film transparencies was fixed for the duration of the study by setting the illumination source gain control. The video camera was set to optimal focus, F stop, and vidicon gain levels. The rigidly mounted TV camera had a zoom lens control through a separate servo system that was controlled by the experimenter via discrete hard wired settings.

Atmospheric attenuation was simulated by the control of video gain. The gain factors within the RPV simulator system were non-linear in the operating range used to display the images, and it was possible to change target-to-background contrast sufficiently to simulate atmospheric attenuation for visibilities ranging from 40 km to 5 km. The contrast values were repeatedly checked throughout the testing period with a photometer on standard targets. The actual contrast values measured at the monitor with a photometer were specified to be 0.18, 0.40 and 0.70 for a background luminance of 10 fL and an inherent target contrast of 0.85. Therefore, with an average background scene luminance of 10 fL, the target luminances were 8, 6, and 3 fL for the 5, 20, and 40 kilometer visibilities, respectively. In all cases, the contrast was varied such that the background remained constant, and the target was made brighter to decrease contrast. This process simulated actual atmospheric

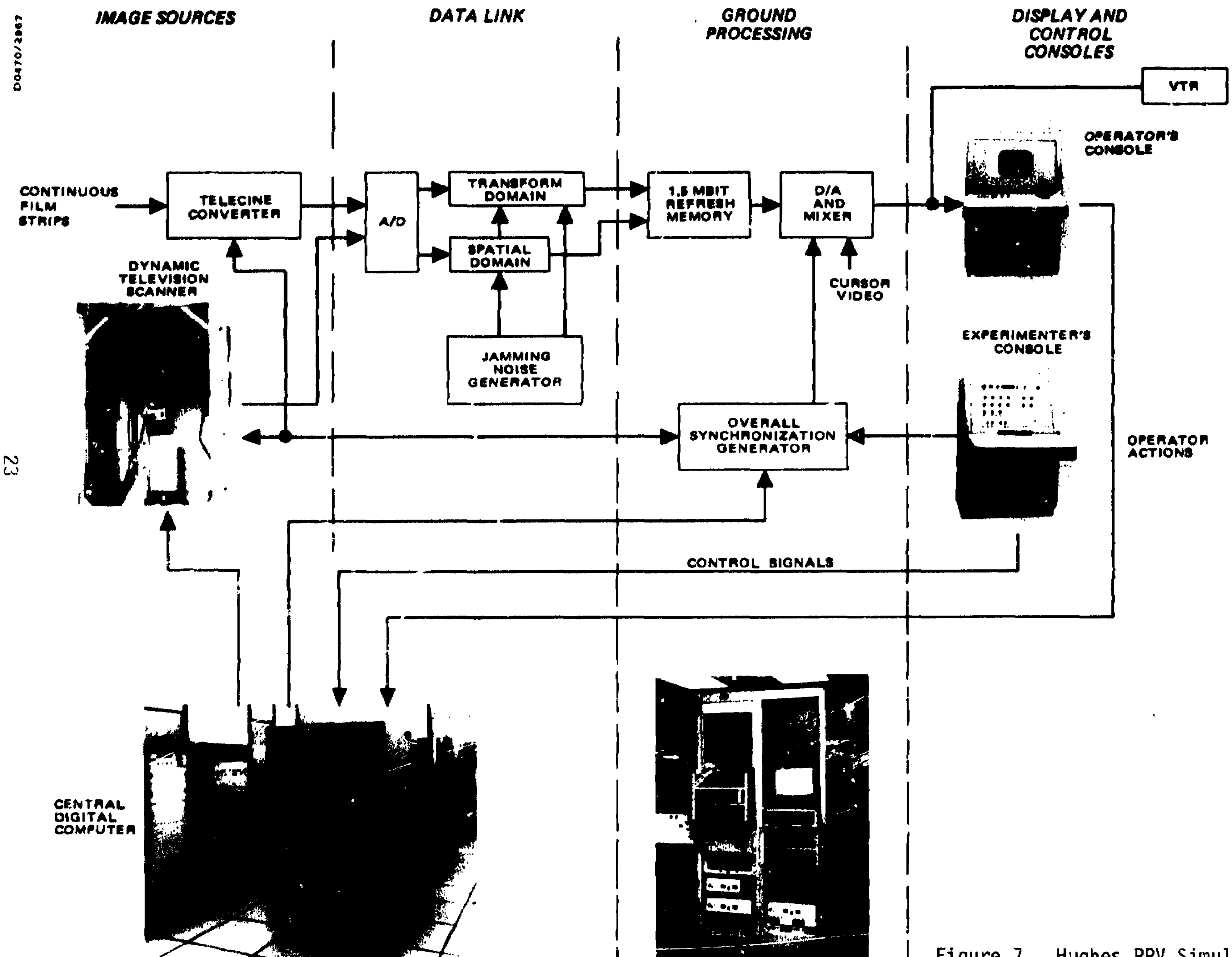


Figure 7. Hughes RPV Simulator

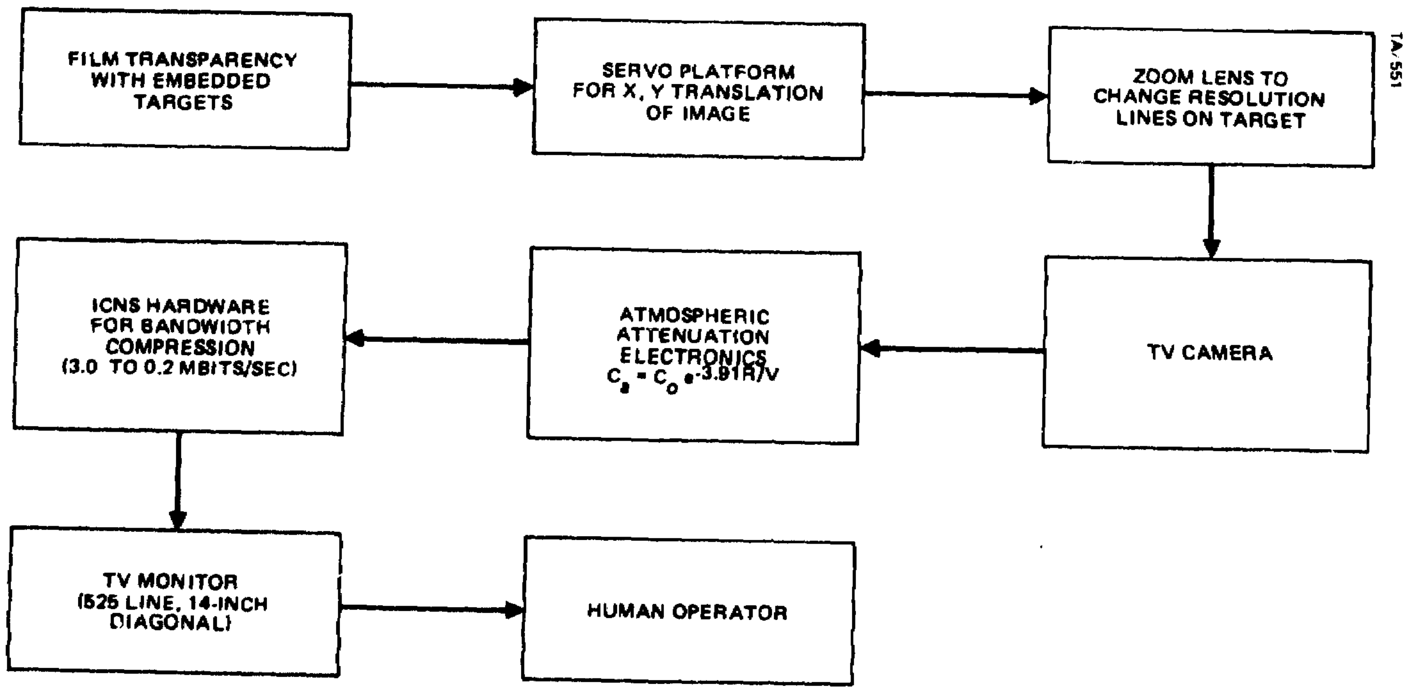
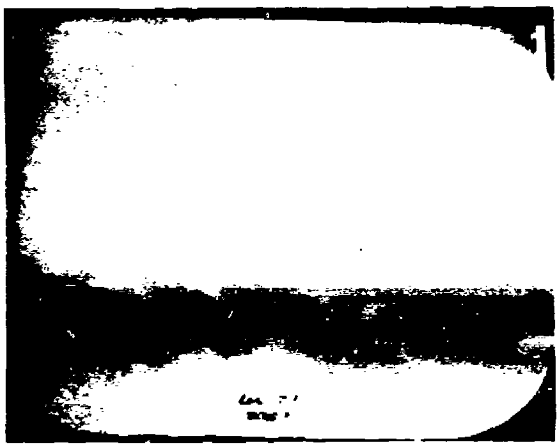


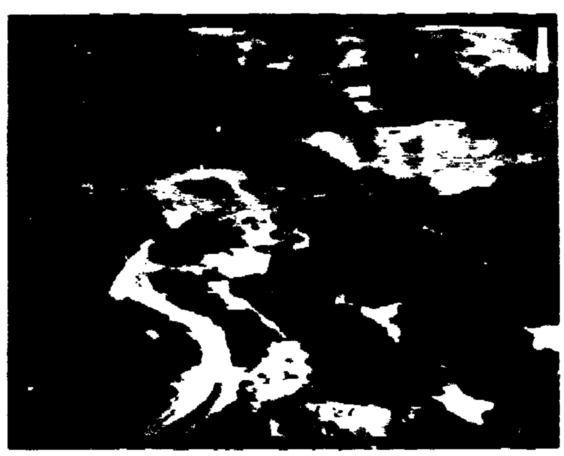
Figure 8. Block Diagram Of Simulation Implementation

attenuation, in which the contrast reduction is caused by increased reflectance of light from intervening air particles (haze) with a perceived whitening of a dark target. Examples of the three atmospheric attenuation levels are shown in Figures 9 and 10.



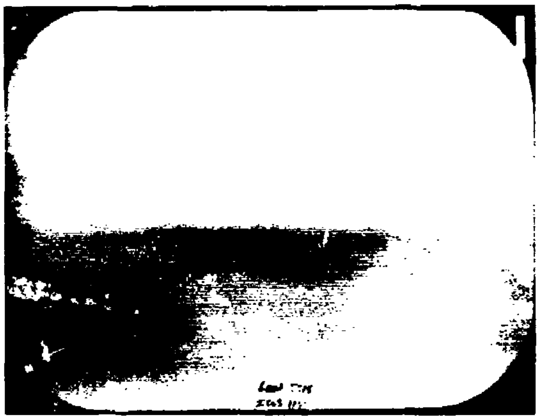
a. 0.2 Contrast

b. 0.4 Contrast

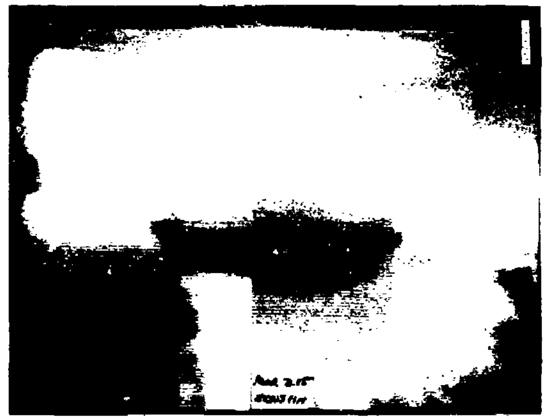


c. 0.7 Contrast

Figure 9. Example Target Scene At The Three Atmospheric Attenuation Levels With 3 TV Lines Across Targets



a. 0.2 Contrast



b. 0.4 Contrast

c. 0.7 Contrast

Figure 10. Example Target Scene At The Three Atmospheric Attenuation Levels With 47 TV Lines Across Targets

The video signal from the camera was input to the ICNS for bandwidth compression processing. The interface between camera and ICNS unit was closely monitored. The video signal input to the ICNS unit was maintained within correct specifications by specially designed monitoring and regulatory components in the RPV simulator system. The processed video signal was input to the RPV simulator monitor and refreshed at 30 Hz.

The RPV simulator monitor is a 14-inch diagonal display mounted in a control console, as shown in Figure 11. The test subjects, acting as RPV operators, were seated at the console. A chin rest was secured to the console

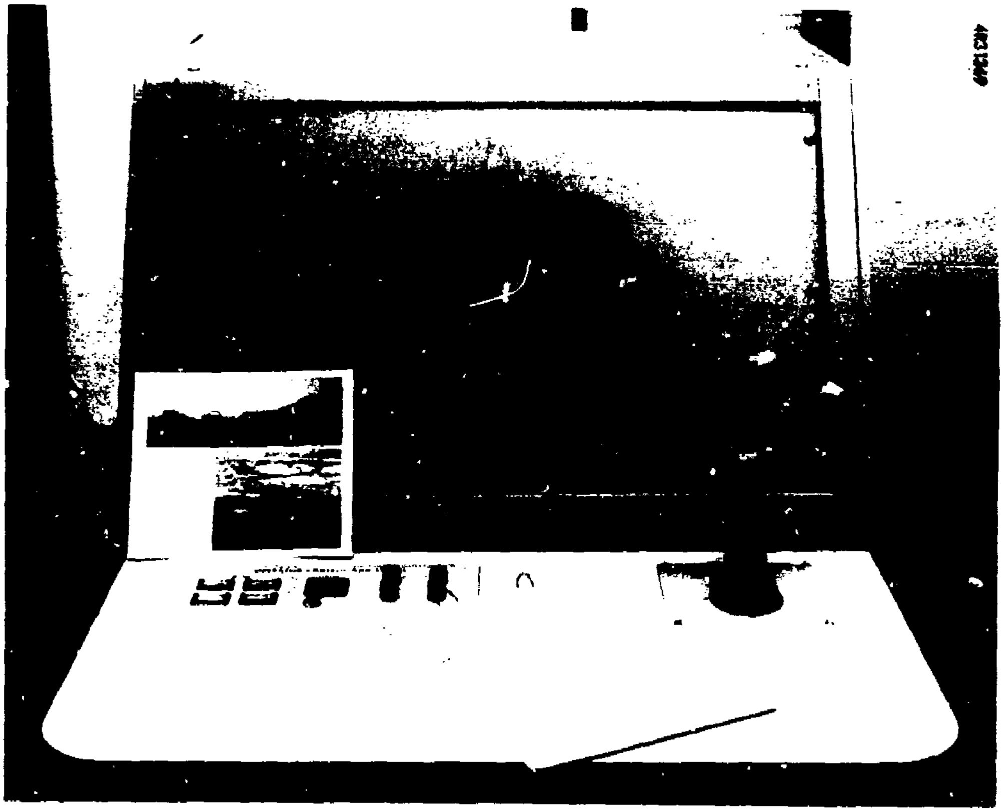


Figure 11. Operator's Console

25 inches from the display to achieve a fixed, known viewing distance. The simulation was physically configured such that the subjects could not read switch settings or view imagery selection during the course of the study.

Software Simulation

On-line computer control of the simulation was unnecessary, but software was required to establish the conditions and switch settings needed for each of the 180 test trials that were run. The images, switch settings, and response codes for each trial were printed for each subject, so that operations performed by the experimenter would have minimal errors. The principal use of software was to execute a randomization algorithm for the zoom step procedure. Each step in magnification was shown in order, but the center point of the display was randomized about the target location to avoid cueing the subject. A zoom procedure with the target always at the center of the display or a fixed locus from display center would yield artificially low estimates of target detection line criteria.

Imagery Preparation

The imagery preparation for the study was directed toward an accurate representation of target and background conditions that have been projected for the RPV system. The imagery processing included six stages. First, a set of background imagery was selected which met the following criteria: 1) the terrain and cultural features present in the images had to be representative of Eastern European (Fulda Gap) terrain, 2) the images had to have high resolution and adequate contrast to match the high image quality obtained in photographs of target models (to avoid unrealistic mismatches between the two), and 3) the backgrounds had to have been photographed under sensor-to-target geometric relationships which would match RPV conditions (i.e. correct field of view, range, altitude, depression angle). The Hughes Display Systems Laboratory archives had a series of aerial photographs which fit the requirements. These were taken during a single sortie for Operation SNOFEX over Upper New York State under clear atmospheric conditions. A preliminary set of 30 images was selected which had varying scene content, but was consistent in terms of sensor-to-ground geometry. The original 41-degree field of view was reduced to 15 degrees and the horizontal locus for target placement was systematically varied across image frames.

The second step in imagery preparation was the sorting of the candidate images into complexity categories by Marine photographic interpreters. The outcome of the rating study was a set of 15 images which represented high, medium, and low complexity levels. The images also were rated for local area complexity, using a 5 by 5 cell grid. Each cell was rated individually for complexity and difficulty of target detection by the interpreters. Thus, the experimenter could place a target at any point along the correct range locus in areas that would presumably make detection easier or more difficult. This procedure produced two independent estimates of background complexity: a global measure and a local one. The target could be placed in an easily detectable area within a highly complex scene, or vice versa.

The target embedding was accomplished by a visual target-to-background registration procedure. The positions of the group of 10 targets on each of the backgrounds were draw on clear acetate overlays; the overlays were then taped over the back of a Linhoff (180 mm) camera, which has a glass projection surface. When the scale of the overlay, target model, and background image were equal, then the photograph of the target models could be accurately reproduced and composited on the background with accurate registration. By viewing the vehicle models through the Linhoff camera, the position, aspect angle, size (range), and simulated shadow could be adjusted. The shadow was created by a high intensity lamp, adjusted to the correct incident angle. The target models were plastic, military miniatures at HO (1/72) scale. The camera was positioned at the correct height and depression angle relative to the models to simulate the RPV altitude and sensor depression angle.

The targets were photographed first with the groups of 10 targets, and then nine were removed, leaving a single target of interest which was then photographed under identical conditions. Therefore, each background was paired with the two target numerosity conditions with identical position and camera settings.

The target negatives were processed, enlarged, any extraneous objects in the negative were eliminated, and then the correctly scaled final film positive of the target was used as an overlay on the background. The equivalence of position, scale, contrast, and image quality between the targets and backgrounds for the different versions of each scene were confirmed by measurements made on the images displayed on the simulation television monitor.

The imagery was modified for the fixed coverage part of the study. To keep the ground coverage constant through the zoom range, the background was masked with a fixed window around the target. The window size was determined by the smallest coverage in the 15 step zoom series: 58 feet at 47 lines across the target. The window was physically implemented using a vellum overlay on the photographic film which had a correctly scaled opening over the target area. The vellum allowed light to pass through, but acted as a low pass spatial frequency filter so that the masked surround had gray scale and some low frequency features but most terrain features could not be identified. The resulting low pass filtered surround was preferred to a black surround which would have created a large change in the distribution of luminance across the display when compared to the conditions of the variable coverage study.

Experimental Design

Six variables were investigated in the variable coverage part of the study as follows:

Bandwidth compression--6, 3.2, 1.6, 0.8, and 0.4 bits per pixel
Atmospheric attenuation--0.18, 0.40, and 0.70 contrast
Target numerosity--single targets and groups of 10 targets
Global background complexity--low, medium, and high rated complexity
Target type--APC, tank, SP-gun, 2 1/2-ton truck, and jeep
Target aspect--broadside and 45-degree forward quartering.

If each variable were fully crossed with all others, an experiment with 900 conditions for a single replication would be required. A more economical design was used in which all levels of the six variables were evaluated. The design was generated with two constraints operating. First, the detection/recognition task requires that the same scene (target and specific background image) cannot be shown to a subject repeatedly, because the subject can recall specific scenes and a learning effect will bias the results. Therefore, conditions were assigned to subjects in a manner that avoided repeated presentations of the same images. The second constraint was that the number of subjects required and the testing time required for each subject could not be excessive.

Figure 12 is a diagram of the experimental design used. In this analysis of variance statistical model design, the bandwidth compression, atmospheric attenuation, and target numerosity variables are fully-crossed, such that each value is paired with every other value. The target numerosity variable is between subject groups; six subjects received single targets, and six received groups of 10 targets. The bandwidth compression and atmospheric attenuation variables are repeated measures; all subjects saw all combinations of them.

The subjects were assigned to the nine atmospheric attenuation-global complexity combinations in a latin square design. Each subject received three out of the nine combinations. Any given subject received all three values of atmospheric attenuation and all three values of global complexity, but only

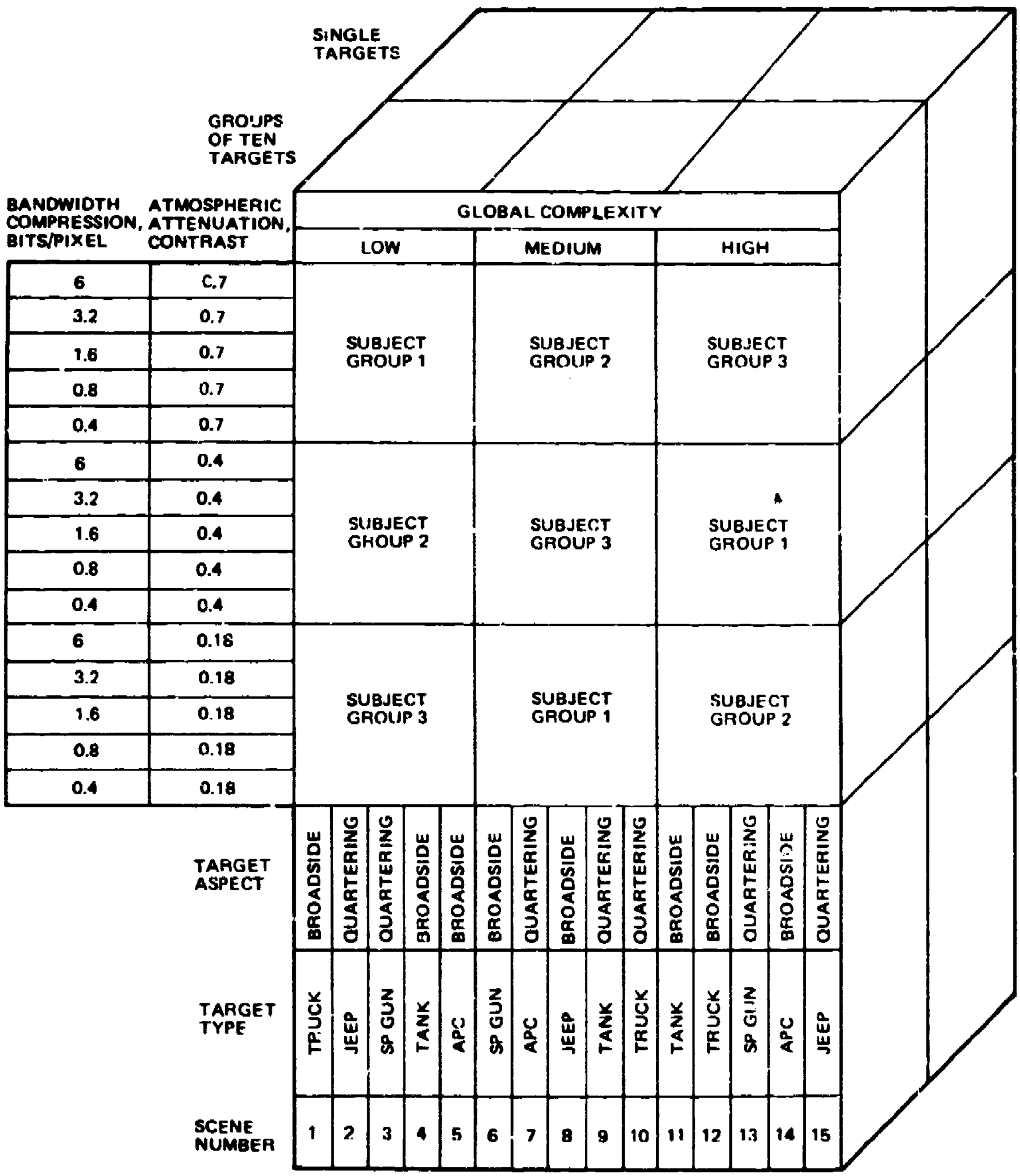


Figure 12. Experimental Design For The Variable Coverage Study

one third of the nine combinations. There were six groups of two subjects each. Figure 12 shows three of the subject groups that represent the groups of 10 targets target numerosity between-subjects part of the design. The latin square design was necessary to avoid repeated presentations of the same images.

The target type and aspect angle conditions were assigned to images in a balanced fashion with respect to the global complexity value of each image. For example, there were five images having high global complexity; images within that group were assigned one target type and one aspect angle each.

The design made it possible to evaluate the effects of all six variables and most of the two-way interactions between pairs of variables. The local complexity rating for each target placement in the 15 images was recorded for analysis, but it was not included in the overall design as a factor.

Each subject was shown 15 images. The images were presented in blocks of five, with all examples of one global complexity value being shown in a block. Within a block, the images were shown in randomized order. The bandwidth compression values were counterbalanced such that each compression condition was shown equally often in each ordinal position in the series.

The experimental design for the fixed coverage part of the study was the same as single target half of the variable coverage study experimental design. While the global complexity parameter was present in the design, it was ineffective because of the small terrain coverage of the target scenes.

Subjects

The subjects used in the study were members of the Hughes Display Systems Department technical and administrative staff. Twelve subjects were used in the variable coverage part of the study, and six subjects were used in the fixed coverage part of the study. All subjects had 20/20 or better corrected or uncorrected visual acuity as measured with the Snellen Chart. All subjects were familiar with video displays of tactical target imagery, and all had previously participated in similar operator performance research.

Study Procedure

A testing session consisted of a training phase followed by the data collection trials. A subject was first given the visual acuity test and then shown the simulation apparatus. The subject was given a general instruction sheet which explained the problem under investigation, described the RPV system, and explained his task in the study.

The experimenter demonstrated the conditions that were included in the study with a training image that had a high complexity background and a group of 10 targets. The five bandwidth compression levels were first shown at high contrast. The three contrast levels associated with atmospheric attenuation were then shown. The target subtense range was then demonstrated at the 15 discrete zoom steps. Finally, the five target types were pointed out to the subject in the training image at highest magnification. The tank and SP-gun were compared to insure that all subjects could discriminate the two similar vehicles. The two aspect angles were also shown in the course of indicating target types.

The training phase was completed with practice trials. Practice trials were run with high contrast, uncompressed images with emphasis on the detection and recognition tasks and the required responses. Questions about response criteria and correctness of response were answered during this phase, but no feedback was given during the data collection trials.

Data collection trials were conducted in the same way for all subjects. The experimenter set switches for the bandwidth compression and atmospheric attenuation conditions on the console, mounted the photographic image in the servo platform, set the zoom servo to the initial position, and unblanked the display when the subject was ready. The display was blanked between the presentations of each magnification step in a trial. A response was required from a subject at each zoom step. At the start of the series, a subject answered "Yes" or "No" to the implied question, "Do you see anything that looks like a target?". A time limit was not set, but a subject was prompted after 20 to 30 seconds; subjects generally responded before that time. If the response was "Yes" the subject pointed to the candidate object(s) and gave a confidence rating of 1 (low) to 5 (high) that the object was in fact a target. After a total of three correct detection responses or a correct detection with high (a 4 or 5 rating) confidence, the target to be recognized was positioned in the center of the display and the subject was prompted for a recognition response, which consisted of the target type name and another confidence rating as to the correctness of the response.

The subjects were briefed that recognition responses could be made at any time. Some correct recognition responses occurred concurrently with correct detections. The subjects were not told when they were correct. The number of correct recognitions which could be given by a subject before the trial was terminated was varied to minimize cueing effects. If the 15 magnification steps were completed without a correct detection or recognition response, the trial was coded as a missed target.

The test session was ended with a debriefing of the subject. The experimenter also answered any further questions about the RPV system or the study tasks.

The procedures for the fixed coverage part of the study were the same as the variable coverage study with modifications in the instructions to account for the small fixed coverage window. Five "catch" trials without targets were also included. The "catch" trials were added in an attempt to introduce uncertainty in the narrow coverage images and thereby make the subjects more cautious about making a detection response. The catch trials were inserted into the data collection sequence either before or after trials having the same bandwidth compression and atmospheric attenuation values.

Performance Measures

Each trial was conducted as a series of responses to the 15 zoom steps. The steps at which the first correct detection, the third correct detection, the first false alarm, last false alarm, and first correct recognition occurred were recorded. The confidence ratings for the five kinds of responses were also recorded. Althougn this resulted in 10 dependent measures being recorded for each trial, the performance measures of primary interest were the first correct detection and first correct recognition. These two measures are used to describe the results obtained in the study.

The zoom steps were converted to line criteria units. Table 2 shows the 15 steps and the number of TV lines across the target height associated with each step. These values were confirmed through measurements of a tank target in the simulation. The target height was defined for tanks; variations between target types were taken into account in the analysis.

TABLE 2. ZOOM STEP, TV LINES ON TARGET, AND TARGET SUBTENSE

Zoom Step	TV Lines On Target	Target Subtense, Arcminutes
1	3.0	14.3
2	3.3	15.8
3	3.5	17.1
4	3.8	18.4
5	4.1	19.7
6	4.4	21.1
7	4.8	23.0
8	5.4	26.3
9	6.3	30.3
10	7.4	35.5
11	9.3	44.8
12	11.9	54.7
13	16.4	79.0
14	24.5	118.5
15	47.7	230.0

RESULTS AND DISCUSSION

The TV lines at detection and recognition response data collected during the study were sorted and stored in magnetic disk files on the Hughes Amdahl computer system, and data analysis was performed using Biomed and SAS statistical packages. Analyses of variance were used to test for reliability of differences obtained from the levels of the variables studied. The analysis of variance summary tables are contained in Appendix A. A priori t-tests were used to test for reliability of differences among pairs of conditions. The results are organized by the variables studied--first for the variable coverage part of the study followed by the fixed coverage part of the study.

Variable Coverage Study

Bandwidth Compression

The effect of bandwidth compression on both target detection and target recognition performance was highly statistically reliable. The probabilities that the obtained differences among the five levels of bandwidth compression could occur by chance was 0.0016 and less than 0.0001, respectively, for target detection and recognition performance. Figure 13 shows the mean number of TV lines required for target detection and recognition as a function of bandwidth compression averaged across all other study conditions. There was no appreciable degradation of performance between 6.0 and 1.6 bits per pixel. An average of 4.7 TV lines was required for detection and 9.3 TV lines for recognition for three highest bit per pixel levels. Performance was degraded at 0.8 bit per pixel, 7.5 and 13.2 TV lines for detection and recognition, and continued to degrade at 0.4 bit per pixel, 12.5 and 22.3 TV lines for detection and recognition. A priori t-tests showed that the 0.4 bit per pixel compression required significantly greater TV lines across targets than all other compression levels, and that 0.8 bit per pixel compression was significantly poorer than 1.6 bit per pixel compression.

These findings are consistent with the earlier Naval Ocean Systems Center research, where it was found that performance started to degrade between 1 and 2 bits per pixel. A statistically reliable interaction between bandwidth compression and target numerosity was obtained. This interaction will be discussed a little later.

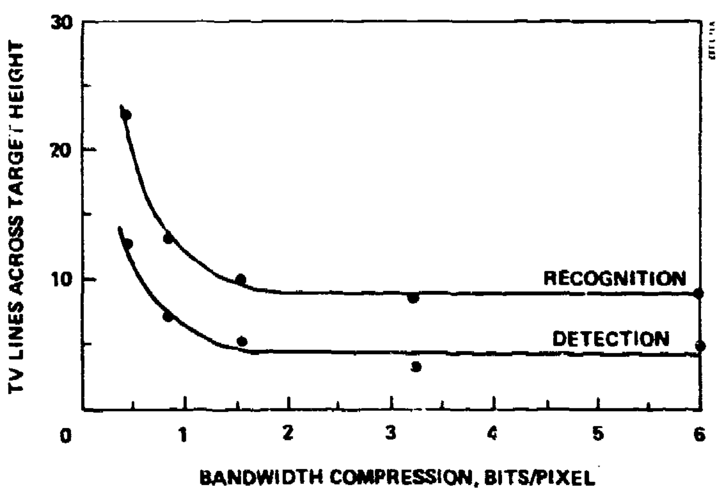


Figure 13. Effects Of Bandwidth Compression On Operator Target Detection And Recognition Performance

Target Numerosity

Groups of 10 targets were significantly easier to detect and recognize than single targets as shown in Figure 14. Single targets required 10.5 and 18.3 TV lines for detection and recognition compared to 3.3 and 7.0 TV lines for detection and recognition with groups of 10 targets. The probability that the performance difference between single targets and groups of 10 targets could occur by change was less than 0.0001 for both target detection and target recognition performance.

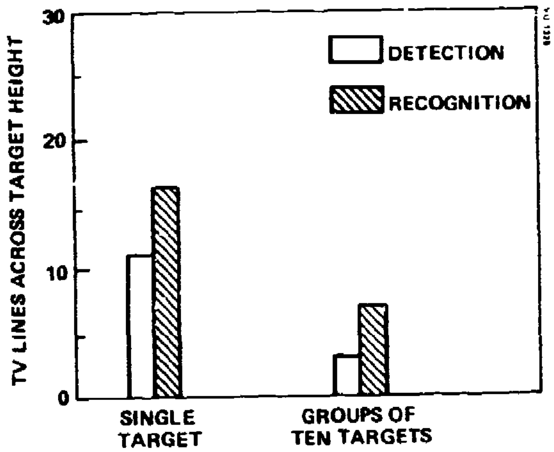


Figure 14. Effect of Target Numerosity On Target Detection And Recognition Performance

The interaction between bandwidth compression and target numerosity is shown in Figures 15 and 16 for target detection and target recognition performance, respectively. The interaction was reliable at the 0.002 and 0.057 probability levels for target detection and target recognition.

Figure 15 shows that bandwidth compression had no affect on the operators' ability to detect groups of 10 targets. The number of TV lines required for detection ranged from 3.1 TV lines to 3.5 TV lines. Apparently, such large groups of targets are so easy to detect that operator performance is resistent to the image quality degradation caused by bandwidth compression. Single targets, on the other hand, are much more difficult to detect in real-

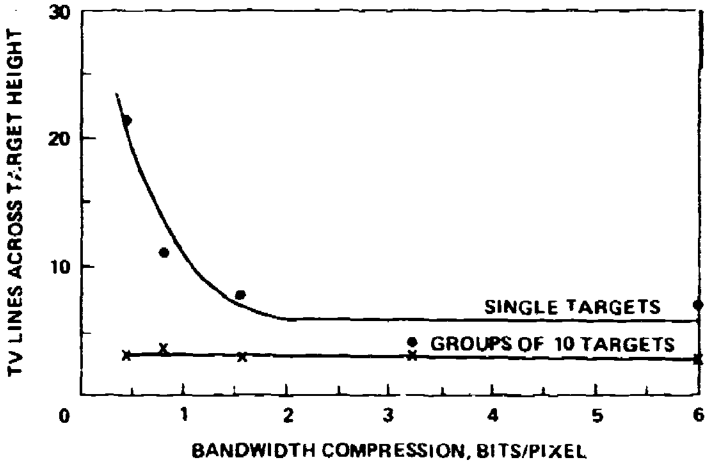


Figure 15. Interaction Between Bandwidth Compression And Target Numerosity For Target Detection Performance

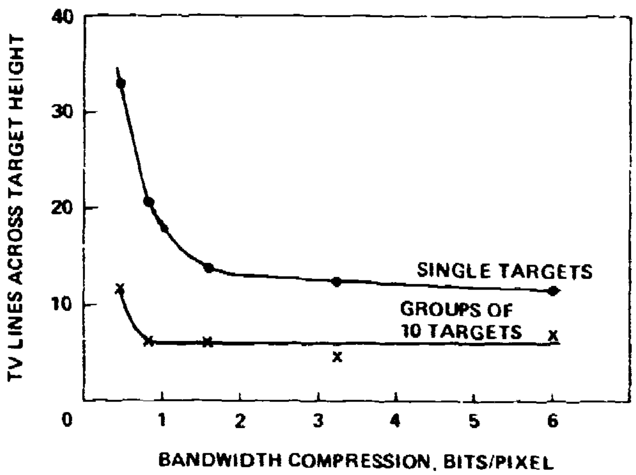


Figure 16. Interaction Between Bandwidth Compression And Target Numerosity For Target Recognition Performance

istic background scenes, and the image quality degradation caused by higher bandwidth compression levels makes the operator's task more difficult as reflected in a greater number of TV lines required for detection.

The interaction between bandwidth compression and target numerosity for target recognition performance was weaker than that obtained for target detection, as reflected in the lower statistical reliability ($p = 0.056$). As shown in Figure 16, there was no degradation of recognition performance for groups of 10 targets until 0.4 bit per pixel compression was reached, while single target recognition performance was degraded at 0.8 bit per pixel.

The reason recognition performance degrades later with groups of 10 targets was probably because of a carryover effect from target detection. Since groups of 10 targets were detected sooner, they tended to be recognized sooner. It is also possible that the presence of 10 targets provided additional cues to the subjects in the study that were not present with single targets. Since the subjects knew the five classes of targets and there were size differences among the five target types, they could use this information to help them recognize the one target out of the group of 10 in the center of the display which they were required to classify (recognize). In the single target case, there were no such comparative cues.

Atmospheric Attenuation

As shown in Figure 17, atmospheric attenuation (contrast) had no appreciable affect on operator target detection or target recognition performance. Nor was there an interaction between atmospheric attenuation and bandwidth compression, which was the primary motivation for including atmospheric attenuation as a variable in the study.

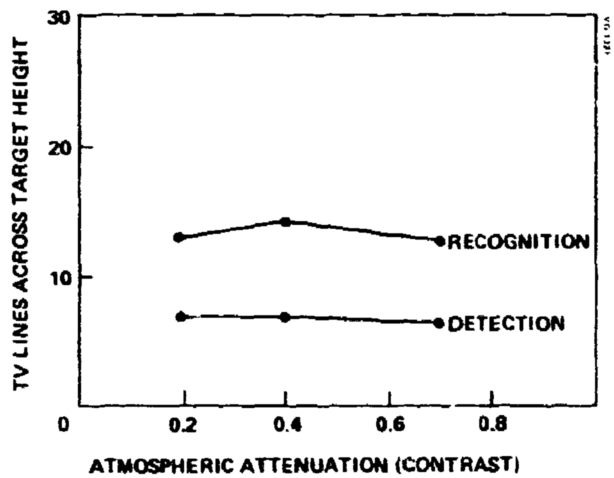


Figure 17. Effects Of Atmospheric Attenuation (Contrast) On Operator Target Detection And Recognition Performance

The failure to obtain a significant effect of atmospheric attenuation was somewhat surprising, considering the large body of research that indicates target acquisition performance improves as contrast increases. For example, Berstein (1971)[5] found detection of vehicles improved from 35 percent to 78 percent as contrast increased from 0.45 to 0.90. To determine if the strong effect of target numerosity may have hidden any effect of atmospheric attenuation, the data were plotted for both single targets and groups of 10 targets, as shown in Figure 18. The trend for improved performance with higher contrast (less atmospheric attenuation) is evident in Figure 18.

The principal finding with regard to atmospheric attenuation and RPV system design and operation is that whatever influence atmospheric attenuation has on operator performance, it is constant with regard to bandwidth compression. Thus, the level of bandwidth compression selected for the RPV system will work equally well independent of any atmospheric attenuation.

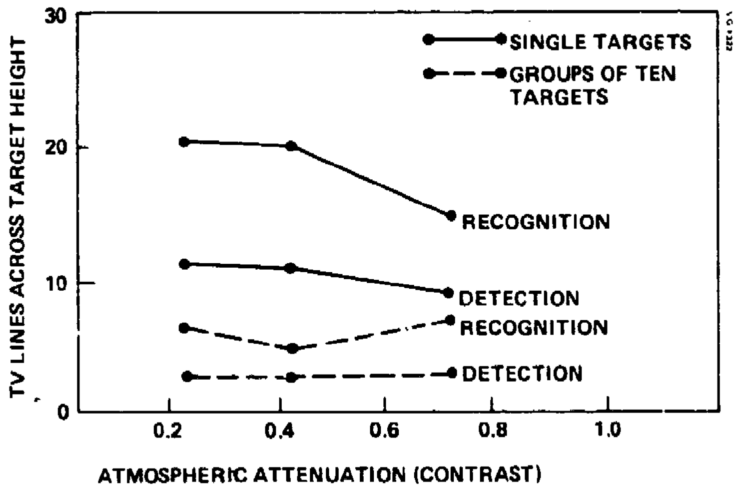


Figure 18. Effects Of Atmospheric Attenuation (Contrast) On Operator Target Detection And Recognition Performance For Single Targets And Groups of 10 Targets

[5]Bernstein, B. R. Detection Performance in a Simulated Real-Time Airborne Reconnaissance Mission, Honeywell, Inc. Systems and Research Center, Minneapolis, Minnesota, T-279(R), 1971.

Global Complexity

The three levels of global background complexity as established by the Marine image interpreter ratings produced nearly equivalent levels of operator performance. Figure 19 shows the main effect of global complexity.

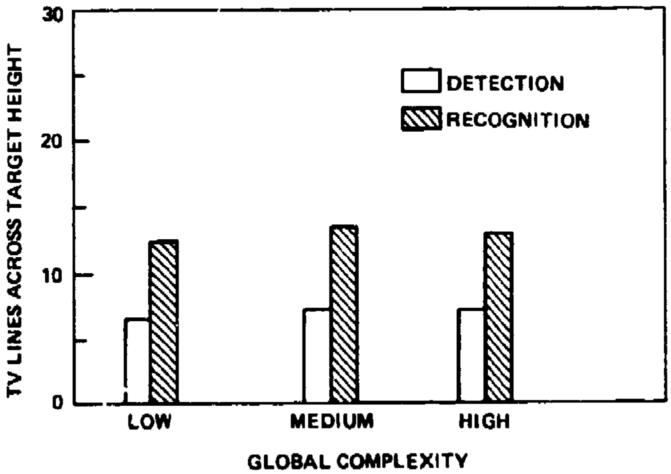


Figure 19. Effects Of Global Background Complexity On Operator Target Detection And Recognition Performance

There were significant differences among the 15 scenes used. One of the medium complexity scenes and one of the high complexity scenes resulted in significantly ($p<0.01$) poorer performance than the other scenes.

Scene complexity has proven to be a difficult factor to describe, either by quantitative image metrics or expert judgment. This study proved no different.

Target Type

While there were small differences in detection and recognition performance among the five target types, the differences were not statistically reliable ($p = 0.40$). The trucks and jeeps tended to be more difficult to detect and recognize than the APCs, tanks, and SP-guns. The mean number of TV lines at target detection and target recognition for the five target types are shown in Figure 20.

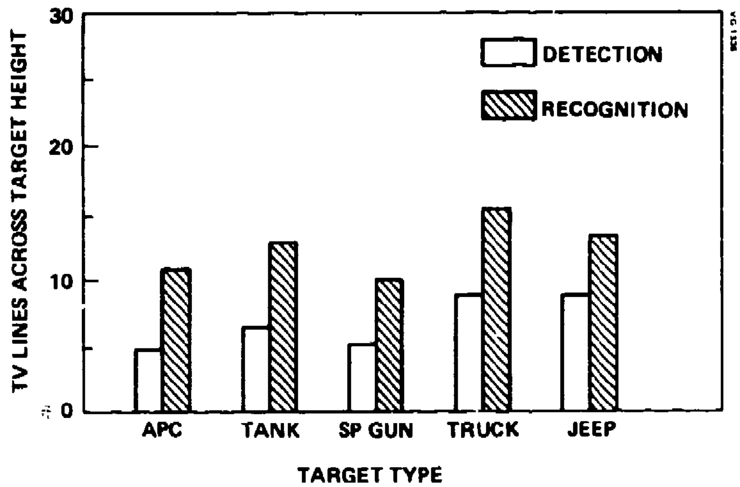


Figure 20. Effect Of Target Type On Operator Target Detection And Recognition Performance

Target Aspect

Targets viewed broadside were significantly easier to detect and recognize than targets seen at a forward quartering aspect, as shown in Figure 21. For target detection, broadside targets required an average of 4.7 TV lines compared to 9.3 TV lines for the forward quartering targets. For target recognition, broadside targets required an average of 9.1 TV lines compared to 16.7 TV lines for forward quartering targets. The differences between the two target aspects were reliable at the 0.002 and 0.0001 probability levels for target detection and target recognition, respectively.

Fixed Coverage Study

The single targets used in the fixed coverage part of the study were always detected at the first zoom step when there were 3 TV lines across the targets' height. The small fixed coverage eliminated the need for any operator target search; hence, there could be no meaningful target detection performance data in this part of the study. The results are therefore presented for target recognition only.

The target recognition results for the parameters investigated--bandwidth compression, atmospheric attenuation, target type, and target aspect--

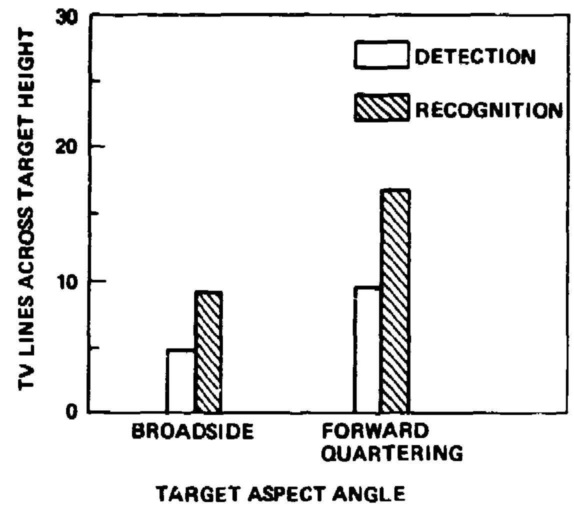


Figure 21. Effects Of Target Aspect On Operator Target Detection And Recognition Performance

largely paralleled the results of the variable coverage study. Bandwidth compression had statistically reliable ($p<0.01$) affects on operator target recognition performance; atmospheric attenuation did not affect performance. Jeeps and trucks were again more difficult to recognize than APCs, tanks, and SP-guns. The effect of target type was statistically reliable in the fixed coverage study ($p=0.026$). Figure 22 shows the main effect of target type on operator target recognition performance. The forward quartering target aspect again required more TV lines for recognition than the broadside target aspect; however, the statistical reliability was not as large ($p=0.067$) as in the variable coverage study.

A comparison of operator single target recognition performance at the five levels of bandwidth compression studied for the variable and fixed coverage parts of the study is shown in Figure 23. It is clear that fewer TV lines were required with the fixed, small, low clutter coverage. The two curves represent two samples of terrain coverage along a continuum, and to understand and describe the relationships among scene coverage, scene clutter, and operator performance would require considerably more work than was done here. For the postulated Army RPV reconnaissance/surveillance and targeting

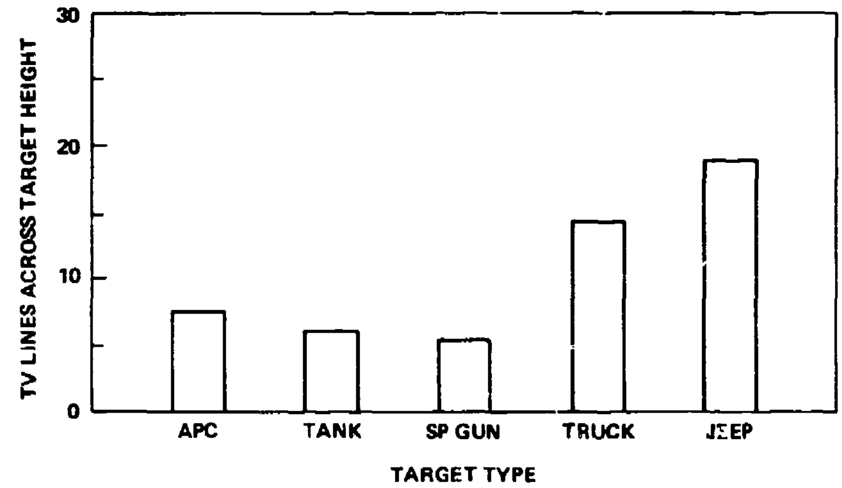


Figure 22. Effect Of Target Type On Operator Target Recognition Performance

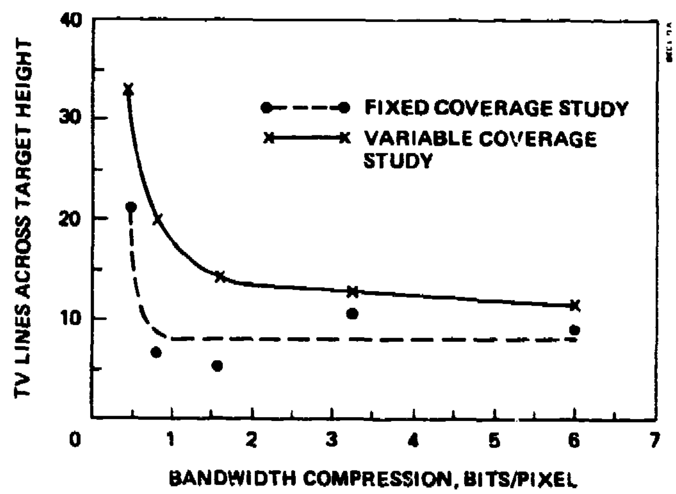


Figure 23. Comparison Of Operator Target Recognition Performance At The Five Levels Of Bandwidth Compression Studied For Variable And Fixed Coverages

missions, target location uncertainty as well as navigation error will be greater than the 58-foot coverage used in the fixed coverage study. The larger uncertainty will dictate a larger field of view, necessitating operator search in a cluttered scene. We, therefore, believe the data obtained in the variable coverage part of the study should be the principal data used for RPV system design.

Figure 24 gives the data we recommend using for RPV bandwidth compression system design for detection of groups of targets, detection of single targets, and target recognition. All of the data are from the variable coverage study. The target recognition curve is from the recognition of single targets data. In the real world, operators would not know there are five classes or targets in a group of vehicles as was the case with the groups of 10 targets used in the variable coverage study. Hence, the single target recognition data where search and detection preceded recognition is the most realistic data to use for RPV system design applications.

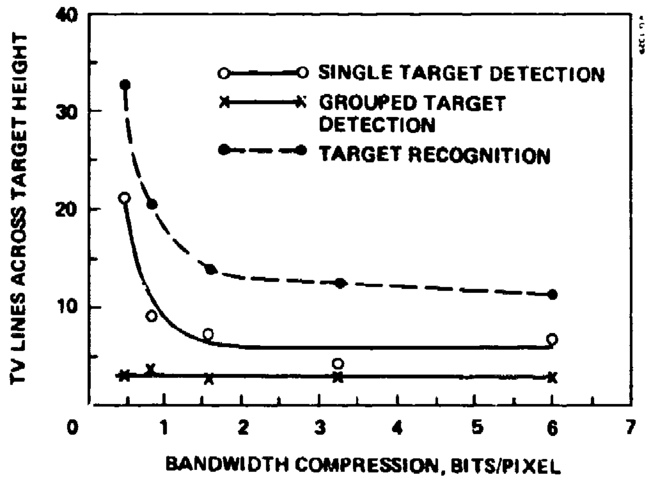


Figure 24. Recommend Bandwidth Compression System Design Performance Curves

Performance Curves

The performance data presented in the preceding discussion of results were for the means of the conditions studied and represent the central tendency of the data. Systems designers, however, are often interested in other points in the data distribution, such as the 90th percentile for example. Furthermore, the plots of the means do not reveal end point probabilities of the various conditions studied. To provide additional data for use by RPV systems designers, cumulative probability plots were prepared for the two most important variables in the study--bandwidth compression and target numerosity. The five plots that were prepared all plot cumulative probability versus TV lines across target height. The curves on the plots are for the variable of interest.

Figure 25 gives the curves for detection of groups of 10 targets at each of the five levels of bandwidth compression studied. It's clear from Figure 25 that groups of 10 targets were always correctly detected (all curves go to a probability of 1.0) and that the differences among the curves are quite small. The performance curves for detection of single targets are shown in Figure 26. It's equally clear from Figure 26 that bandwidth compression had a substantial affect on the subjects' ability to detect single targets. Differences among the 6.0, 3.2, and 1.6 bits per pixel levels of bandwidth compression were relatively small. Performance definitely deteriorated at the 0.8 and 0.4 bit per pixel levels. At 0.4 bit per pixel, only 76 percent of the single targets were detected.

Performance curves for the recognition of single targets at the five bandwidth compression levels are shown in Figure 27. As was the case with detection of single targets, the 6.0, 3.2, and 1.6 bits per pixel compression levels resulted in approximately equivalent performance, and at the 0.8 and 0.4 bit per pixel levels, performance was considerably degraded.

The Electro-Optical and Night Vision Laboratory line criteria data have long been a standard for sensor systems designers.[6] The 6.0 bits per

[6] Ratches, J. A., Lawson, W. R., Obert, L. P., Bergemann, R. J., Cassidy, T. W., and Swenson, J. M. Night Vision Laboratory Static Performance Model For Thermal Viewing Systems, U.S. Army Electronics Command, Night Vision Laboratory, ECOM-7043, April 1975.

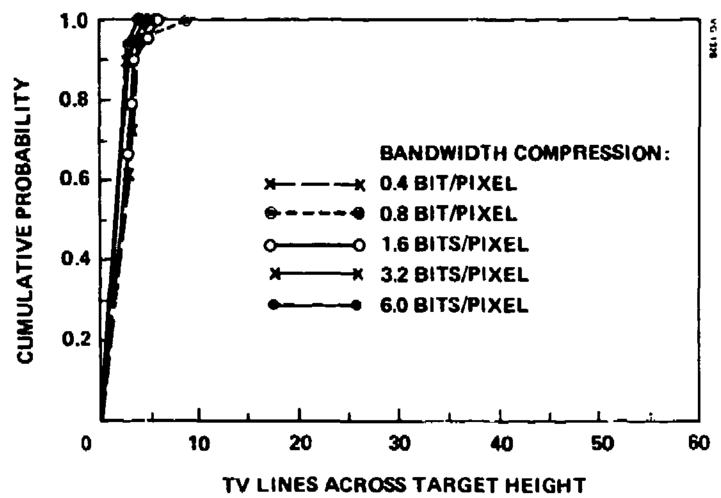


Figure 25. Performance Curves For Detection Of Groups Of 10 Targets

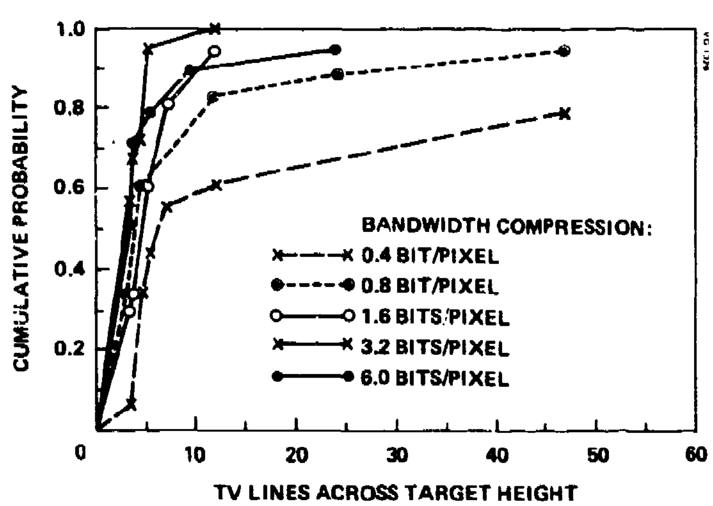


Figure 26. Performance Curves For Detection Of Single Targets

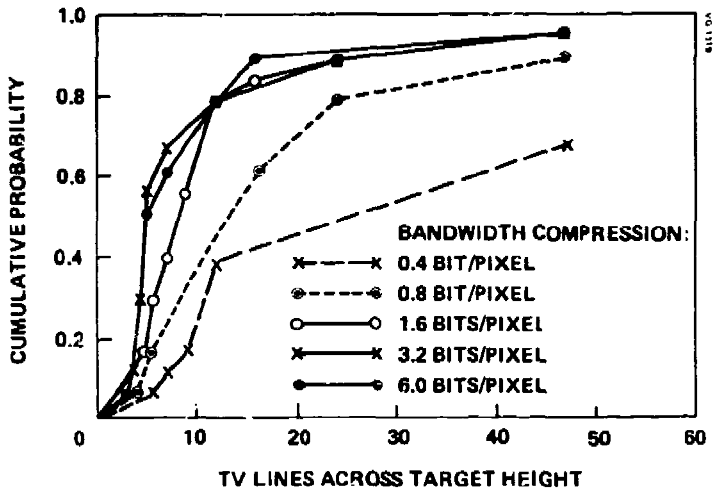


Figure 27. Performance Curves
For Target Recognition

pixel data obtained in this research provides another source of data for detection and recognition of tactical targets in realistic terrain scenes. Figure 28 provides a comparison of the NVL line criteria with the data obtained in this study. The NVL detection criteria curve is very close to the curve for detection of groups of 10 targets from this study. The NVL curve is probably appropriate for hot spot target detection; however, we believe the curve for detection of single targets obtained in this study is more appropriate when single targets must be detected, using both target intensity and shape information.

The target recognition curve obtained in this study indicates fewer TV lines required for recognition than the NVL curve for probabilities up to 0.75. From 0.75 to 1.0, the NVL curve indicates fewer TV lines required for recognition than this study. The failure to attain a recognition probability of 1.0 in this study was due to one instance where a subject failed to detect the target. In all cases where the target was detected, it was correctly recognized. Failures to detect targets do and will occur in realistic tactical environments; hence, performance curves that indicate less than a 1.0 probability are not unrealistic.

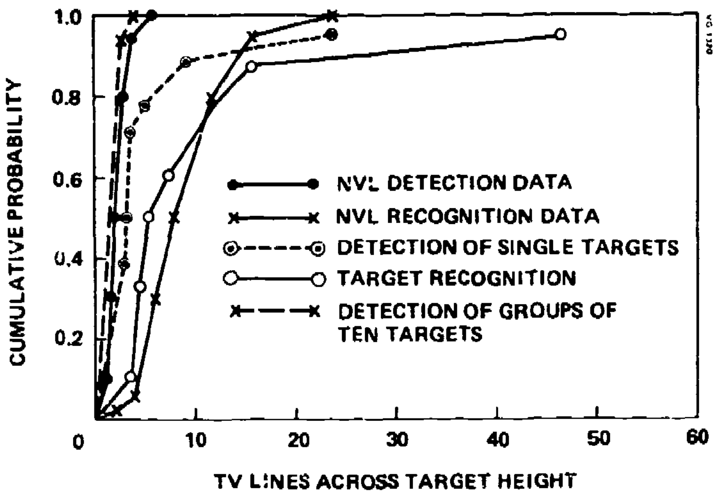


Figure 28. Comparison Of Electro-Optical And Night Vision Laboratory Line Criteria With Data From This Study

SECTION 3

SENSOR SLEWING CONTROL AND VIDEO BANDWIDTH REDUCTION

INTRODUCTION

The surveillance and reconnaissance functions of the Army RPV mission will require the search of both large and small terrain areas. The search function can be accomplished: 1) by preprogrammed flight of the RPV within the desired flight corridors, 2) by using automatic preprogrammed sensor slewing within the sensor's field of regard, 3) by allowing the RPV Mission Payload Operator to manually slew the sensor within its field of regard, 4) by the use of some combination of the above three techniques.

Operator manual sensor slewing would appear to be a desirable design approach because of the adaptive and intelligent behavior that the human operator can bring to bear during the search process. However, the need to operate with reduced video bandwidth in jamming environments can result in a system which is extremely difficult for operators to use.

Video frame rate reduction offers significant potential for video bandwidth reduction. Past research[1, 2, 7] has demonstrated that an 8:1 reduction in video frame rate, from the standard 30 frames per second frame rate, has a negligible affect on RPV operator target designation and tracking performance with conventional rate control systems. The effect of reduced video frame rate on sensor panning (large area sensor slewing), however, has not been investigated. It was the purpose of this study to investigate the effects of video frame rate reduction on large area operator sensor slewing performance. Sensor control modes and sensor field of view were also investigaged to determine how these RPV system design parameters influence the amount of frame rate reduction that might be achieved.

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[7] Fulkerson, D. C., Hershberger, M. L., and Scanlan, L. A. Mini-Remotely Piloted Vehicle Precision Tracking Evaluation, Hughes Aircraft Company, Culver City, California, Hughes Report No. FR-79-27-257, Contract No. DAAB07-78-C-2415, September 1979.

RESEARCH METHODOLOGY

A man-in-the-simulation of the video and control data links between the RPV and the ground control station and the display of sensor video with operator control inputs was used to investigate the effects of video frame rate, sensor control mode, and sensor field of view in this study.

Study Parameters

Video Frame Rate

Four video frame rates were investigated: 0.12, 0.47, 1.88, and 7.50 frames per second. These frame rates provide a bandwidth reduction potential of 256:1 to 4:1, compared to a standard 30 frames per second frame rate. The 7.5 frames per second frame rate was selected as the highest rate based on past research which showed no degradation of operator performance at this level. The lowest rate, 0.12 frame per second, was selected as the lowest feasible RPV video update rate based on the 8 seconds time between frames. The 0.47 and 1.88 frames per second frame rates were selected as intermediate values between the two extremes.

Control Modes

Three control modes were investigated: continuous rate control, image motion compensation, and bang-bang. Table 3 gives the major parameters of the three control modes. Each control mode was empirically optimized with regard to its ease of use to accomplish manual sensor slewing prior to conduct of formal data collection.

Continuous Control Mode

The continuous mode was designed to allow operators to make smooth sensor slewing commands through a high sampling rate (30 Hz) and multi-directional responses from a x-y force transducer hand control. The force transducer responded to thumb pressure in any direction with reference to the x and y axes of the display. The output of the transducer was proportional to the force of the input; processing by a Sigma 5 digital computer introduced a shaping function such that the output was proportional to the square of the

TABLE 3. MAJOR DESIGN PARAMETERS OF THE THREE CONTROL MODES

Design Parameter	Control Mode: Continuous	Control Mode: Image Motion Compensation	Control Mode: Bang-Bang
Hand Control	Force Transducer	Force Transducer	Two-Axis Thumb Switch
Shaping Function	$\Sigma(aX/X/)$ IF $X > k$	$\Sigma(aX/X/)$ IF $X > k$	Fixed Increment (10 Hz) Linear Function Of Time (X), IF $X > k$
Maximum Slew Rate	20°/SEC	20°/SEC	8°/SEC
Fly Over Rate	80 MPH	Ground Stabilized	80 MPH
Symbols	+	+ ◊ ||	+
Polarity	$\pm X$, $\pm Y$; Selectable	$\pm X$, $\pm Y$; Selectable	$\pm X$, $\pm Y$; Selectable
Limits	C($\pm$10 Volts) Where C = Scaling For FOV	C($\pm$10 Volts)	C($\pm$10 Volts)

input. The maximum slewing rate that could be achieved was 20 degrees per second. Within the constraints of the 40-degree field of view imagery used, operators could slew the sensor from one edge of the terrain sample to the other in 2 seconds. There was a constant 80 mph RPV fly-over rate introduced through the software processing. A single crosshair reference symbol was fixed at the center of the display.

Image Motion Compensation (IMC)

The IMC mode used the same force transducer control as in the continuous control mode. The shaping function was the same, and the maximum slewing rate was also 20 degrees per second. The IMC mode was different from the continuous control mode in two major respects: (1) information about the system response to the hand control input was provided and (2) there was complete ground-stabilized image motion compensation which eliminated the vertical fly-over displacement of the terrain.

The system response information was provided by three symbols. The center reference crosshair was stationary as in the continuous control mode. A diamond (◊) symbol indicated the position of the sensor in real time as a function of the current hand control input and transmission delay. A two bar (‖) symbol indicated the position the sensor would take on the next frame update. At low frame rates, operators would see the diamond move away from the center crosshair as they input a displacement signal through the hand control. The two bar symbol would follow, and then stop at the position of the next displayed frame. At the next displayed frame, the point on the image where the two bars had been would be under the center reference crosshair. If no further input had been made, the next displayed frame after that would have the crosshair, two bars, and diamond coincident on the display. At high frame rates, the three symbols would appear to follow each other, with the diamond (new position) leading and the two bars (next frame) following. The result of the three symbol feedback was that the operator knew where he was slewing and what point on the image would be displayed at the next update. The limitation of the IMC mode was that the symbols were constrained to the field of view. Slewing outside of the field of view was possible, but the relevant symbols were driven off the display. In preliminary testing, a 50 percent proportional symbol displacement was attempted, such that a 10-degree sensor displacement command was reflected by a 5-degree displacement of the symbol. This implementation was not optimal, because the operator had to take into account the scaling information while slewing. With the 2:1 scaling, the operator could not point to an area of interest directly, but had to point to a locus halfway to the point of interest.

Bang-Bang Control Mode

The bang-band control mode was implemented with a two-axis thumb switch. The switch could be pushed to the left, right, up, or down with respect to the display. The actual switch orientation was not registered with the display surface, but the axes were rotated to the left by 30 degrees of arc to accommodate thumb action.

The bang-bang mode was an incremental input mode. The response was linear with respect to the number of input pulses generated at the hand control. The hand control input was sampled at 1 z, and each sample was equal to a sensor slewing displacement of 0.80 degree. The maximum slewing rate was therefore 8 degrees per second. Each pulse did not have to originate with a thumb switch displacement, holding the switch in the "on" position would result in an incremental rate. There was a simulated RPV fly-over rate or 80 mph as in the continuous control mode. The operator could slew the sensor by discrete switch pulses in any combination of up, down, left, or right inputs to achieve the desired displacement.

Field Of View

Field of view was investigated to determine its effect on the sensor slewing task--the key question being: is it easier to slew a large field of view over the ground to search an area for a target or to take a greater number of looks with a smaller field of view to search an area. Three fields of view were investigated: 5, 10, and 15 degrees diagonal.

Sensor Slewing Task

While the primary objective of the study s to investigate coarse sensor slewing which required the operators to slew the sensor and search the displayed field of view until the target was in the field of view and detected by the operator, it was also decided to investigate the operators' ability to slew the sensor to place the target near the center of the displayed field of view. This latter task is necessary task preparatory to selecting a narrow field of view for target recognition or target tracking. We henceforth refer to the initial coarse sensor slewing as target search and the second task of slewing the sensor to place the target near the center of the display as target line-up.

Simulation Implementation

The simulation configuration is shown in Figure 29. The system was designed to simulate the three manual control modes, variable field of view,

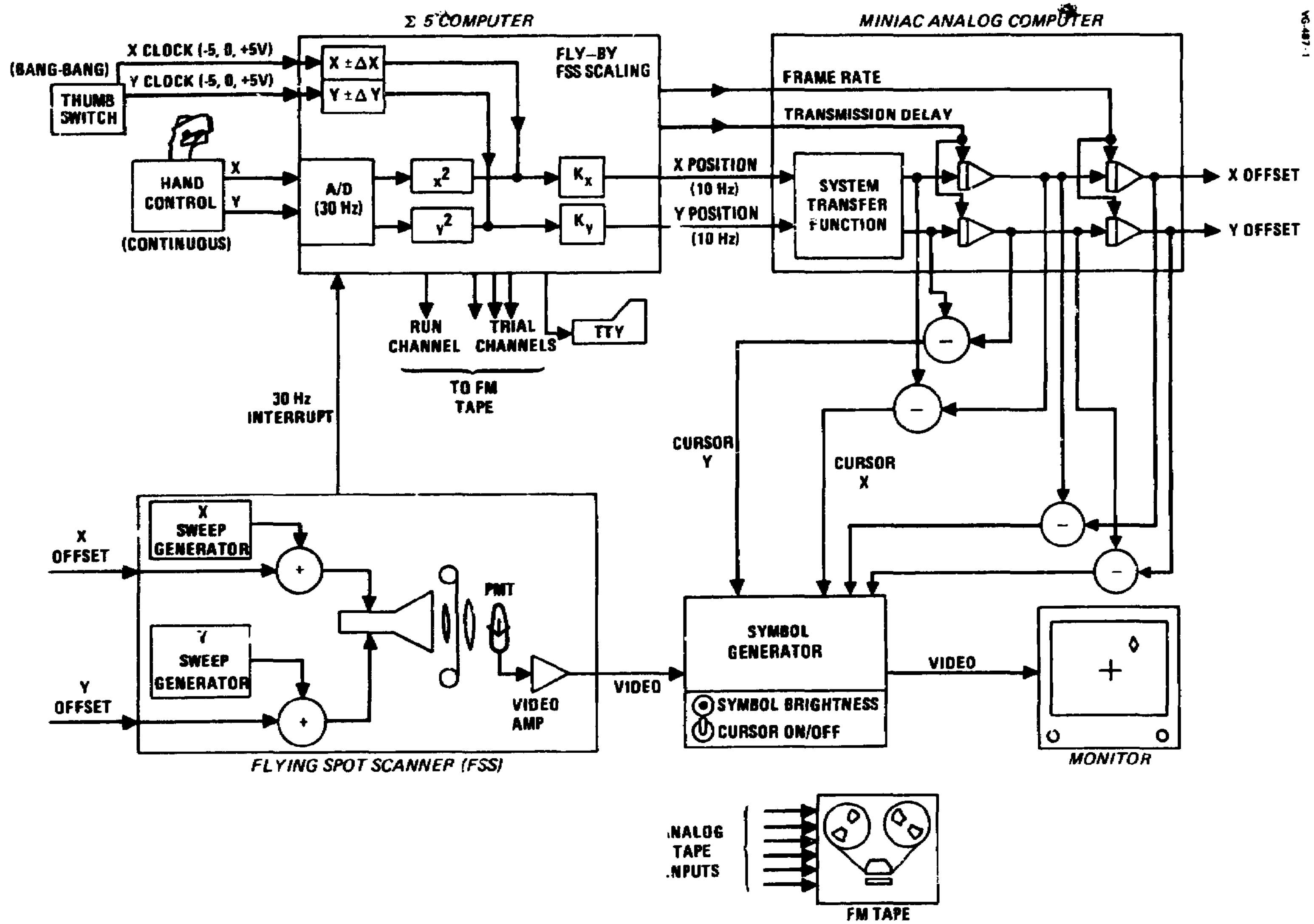

Figure 29. Sensor Slewing Study Simulation Configuration

and the four frame rates as they would function in a RPV system. The data link between the ground station and the airborne sensor, the slewing of the sensor, the reduced video frame rate of the data link to the ground, and the displayed video image at the ground station were the major simulated components. From an operator's point of view, manipulation of the hand control resulted in movement of the displayed image. The displayed system response varied as a function of the control mode, field of view, and frame rate.

The simulation was achieved in the following manner. The terrain was simulated using oblique aerial photographic imagery mounted in a flying-spot scanner (FSS). The FSS could be driven by signals to x and y sweep generators in the horizontal or vertical axis to slew around the world represented by the photographic image. The FSS raster size was reduced such that only a portion of the image was sampled at a given time. The small raster simulated the sensor field of view, and raster displacement simulated sensor slewing. To show a constant-sized world of real terrain and a variable sensor FOV, the film size and FSS raster were scaled with respect to each other. This was achieved by varying the film image size while keeping the raster size constant. Figure 30 illustrates the scaling used.

The x and y offset signals that were used to drive the FSS originated with the operator's hand control input. The x and y displacement signals were sampled at 30 Hz in an analog to digital interface to the Xerox Sigma 5 computer. The digital processing included a shaping function for the x and y inputs, a scaling function to prevent slewing beyond film limits, and a vertical signal input that resulted in simulated RPV fly-by at 80 mph.

The output of the digital processing was interfaced to a Miniac analog computer in which the system transfer function was simulated. The analog processing added the transmission delay and frame rate delays to the signals through sample-and-hold circuits. The processed x and y offset signals drove the FSS. A symbol generator was used to superimpose the reference crosshair on the center of the display. The diamond cursor was generated and driven by signals that were the result of differencing the input and output of the transmission delay sample and hold circuits. The double bar symbol was driven by the differenced input and output of the frame rate delay circuits.

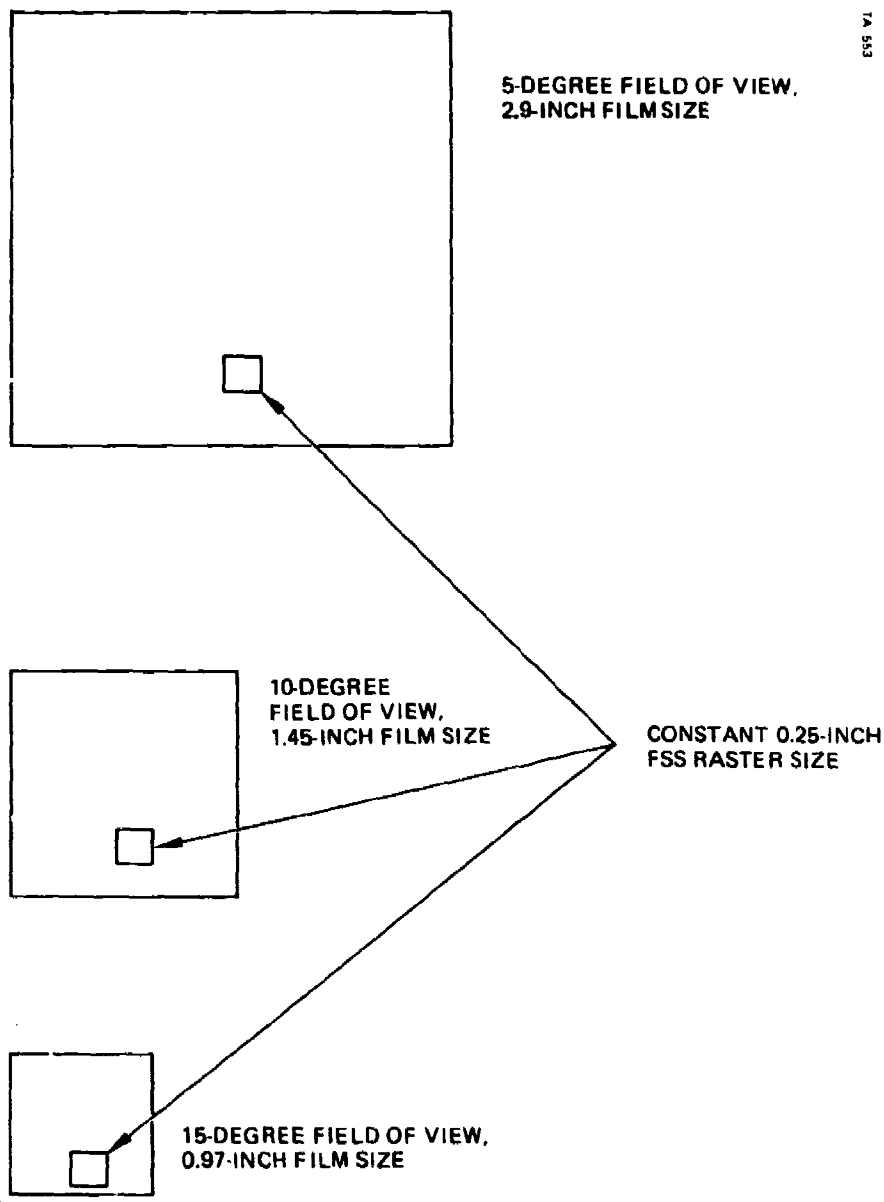

Figure 30. Flying-Spot Scanner/Film Image Scaling For Sensor Fields of View

The video image displayed to the operator was a 14-inch diagonal, 200-TV line image. Between frame updates, a frame was refreshed at a normal 30 Hz rate. The operator closed the simulation loop by responding to the display and making inputs through the hand control.

The hand control was a rigidly mounted hand grip control designed for cockpit applications with multiple switches and transducer inputs that could be manipulated independently. Three control inputs were used in the study: the two-axis thumb switch, the thumb activated force transducer, and a trigger-type switch.

Terrain Imagery

Oblique aerial photography was used to simulate the ground as imaged by a TV sensor mounted on a RPV. The imagery was selected from the same terrain backgrounds used in the bandwidth compression sutdy.

The backgrounds were made into composites to simulate the nearly constant range-to-target that occurs in a RPV fly-by maneuver. In a normal oblique photograph, scale decreases on the vertical axis as the range increases. To approximate the nearly constant range of a fly-by maneuver, selected images were cut so that the middle range was excised and four horizontal strips of terrain imagery were composited into one continuous background. There were no abrupt transitions, because all samples were taken from adjacent terrain areas that were very similar in content. The edges were also irregular so that abrupt transitions were also avoided.

The target was the same throughout the testing conditions for the following reason. In the normal target search and detection process, the operator searches for, and then examines candidate objects before making a detection response. Real targets vary considerably under normal air-to-ground viewing conditions; there are changes in contrast, shadow length, aspect angle, angular subtense, and internal modulation. The detection part of a target acquisition task is therefore highly variable due to target image detectability. The purpose of the sensor slewing study was to investigate the effects of system variables on the sensor slewing component of the task. We did not want the variability inherent in the detection of real targets to dilute the study results.

The target was a rectangular box of high (0.85) contrast. It was scaled such that it subtended the same visual angle under all conditions. For the 5-degree sensor field of view, the target was the equivalent of a 15 by 39 feet rectangle in the real world, or 1.5 times a tank in height and length. The target subtended 1.64 degrees of arc when displayed for all three fields of view.

Eight different composite backgrounds with embedded rectangle targets were prepared. There were four different composite backgrounds with two different target locations for each background. The targets were located along radii of either 20 or 32 degrees from the bottom center of the backgrounds. Figure 31 shows an example of a terrain background with an embedded target.

Figure 31. Example Of 40-Degree Image Scene
With Rectangular Target

Experimental Design

The four study variables--video frame rate, sensor control mode, sensor field of view, and sensor slewing task--were investigated using a fully-crossed split-plot analysis of variance model. Because of potential problems in training and habit interference, control modes was a between-subjects variable. Five subjects were randomly assigned to each of the three control modes. Each of the 15 subjects received all 24 combinations of the four frame rates, three fields of view, and two sensor slewing tasks. The 24 combinations were replicated twice so that each subject received a total of 48 test trials. Frame rates were presented in blocks of six trials. Order of presentation of the frame rates and fields of view were counterbalanced across subjects. The search task was always presented first, followed by the line-up task.

Subjects

The 15 subjects were Hughes technical and administrative staff personnel. All the subjects had 20/20 or better corrected or uncorrected visual acuity as measured with a Snellen Chart.

Study Procedures

The test sessions were conducted the same way for the three groups of subjects. Each subject was given a standard set of instructions to read. The instructions explained the purpose of the study, the general nature of the RPV system, the task, and criteria and suggestions for task completion. The control mode assigned to each subject was described in a separate written information sheet. The written instructions were followed by a standard verbal briefing by the experimenter. The task was first demonstrated with a photographic print to illustrate the sensor-to-ground geometry, the relative sizes of the three fields of view, and for the continuous and bang-bang modes, the direction of vehicle motion.

A subject was then allowed to practice using the hand control to slew the sensor with a training image. The training image was similar to those used in the test set, except that the target was placed close to the start point to simplify search. Each subject was given a minimum of 6 minutes to slew the sensor under each of the four frame rates. Subjects were instructed to develop a search strategy and to maintain that strategy throughout the test. The subjects were also allowed to practice lining up the target or objects of interest with the center of the display (crosshair symbol). Any questions were answered by the experimenter during this training phase.

After the training phase, the task and experimental conditions were reviewed with each subject. Each test trial consisted of a search task portion and a line-up portion. A trial was conducted as follows. The experimenter selected the required field of view and frame rate conditions, and with the subject's display blanked, advanced the photographic film in the FSS to the required image. The start switch and display unblanking switch were onset simultaneously when the subject was ready. The subject then slewed the sensor until he detected the target, and then depressed the trigger switch on the hand control, which put the system in a stop mode. The display was then blanked by the experimenter. If the subject did not find the target, the system automatically entered the stop mode after 3 minutes. With the display blanked, the experimenter set a target reset value to place the target at a known location within the displayed field of view. The display was then unblanked, and the subject slewed the sensor to place the target anywhere under the crosshair symbol in the center region of the display. If the target moved out of the field of view during this phase, the subject was instructed to resume search, reacquire the target, and continue. When the target was under the crosshair, the subject depressed the trigger switch, and the system entered the stop mode. If the subject was not able to position the target under the crosshair within 3 minutes, the system went into the stop mode.

Subjects were instructed to release the hand control and relax between trials. A 5 to 10 minute rest interval was included after the first 24 trials, the first replication, with additional rest periods upon request.

Each subject was asked to read a modified Cooper-Harper rating scale, as shown in Table 4, to evaluate control task difficulty after each block of trials with a given frame rate. Any comments or suggestions about the simulation were summarized and recorded by the experimenter.

Each subject was debriefed at the end of the testing session, and any further questions were answered. The total duration of a session, including the training phase, was about 2 hours.

TABLE 4. MODIFIED COOPER-HARPER RATING SCALE

RATING CLASS	RATING	CRITERIA
SATISFACTORY	1	EXCELLENT, PLEASANT TO USE
	2	GOOD, EASY TO CONTROL, NO ANNOYANCES
	3	GOOD, EASY TO CONTROL, VAGUELY UNPLEASANT CHARACTERISTICS
UNSATISFACTORY	4	ACCEPTABLE, CONTROLS FAIRLY WELL, BUT HAS SOME DEFINITELY UNPLEASANT CHARACTERISTICS
	5	UNDESIRABLE FOR NORMAL OPERATIONS, CONTROL CAN BE MADE ACCEPTABLE ONLY WITH EFFORT
	6	UNACCEPTABLE EXCEPT FOR EMERGENCY, CONTROL IS DIFFICULT AND REQUIRES MUCH ATTENTION
UNACCEPTABLE	7	UNACCEPTABLE EVEN FOR EMERGENCY, CONTROL IS POOR AND REQUIRES FULL ATTENTION
	8	DANGEROUS – INCIPIENT LOSS OF CONTROL
	9	UNCONTROLLABLE FOR MORE THAN SEVERAL SECONDS
	10	LOST CONTROL EVERY TIME – ABSOLUTELY UNCONTROLLABLE

Performance Measures

Time and probability of successfully task accomplishment for both the search and line-up tasks were measured and recorded. Time was measured to the nearest 0.1 second. While a 3 minute task time limit was used in the study, in real-world geometry at an 80 mph RPV speed, it would take 53 seconds to fly over the 40-degree terrain area that was contained in the imagery used. Sensor look-back capability will extend the available time to search along the flight path. A 70-degree look-back capability (70 degrees from nadir) that corresponds to the initial 20-degree sensor forward looking depression angle at the start of a trial is realistic. With such a 70-degree look-back, the total available time for sensor search and target line-up would be 93 seconds. Based on these considerations, analyses of the probability of successful task accomplishment data were performed with a 93 second time limit.

The subjects' evaluation of the difficulty of using the three control modes and the four frame rates was also measured using the modified Cooper-Harper rating scale.

RESULTS AND DISCUSSION

Descriptive and inferential statistical analyses were performed on the target search and target line-up task time data. The probability of successful task completion, and the results of the Cooper-Harper ratings are also shown in graphic plots. Analysis of variance summary tables are contained in Appendix A. The results are presented and discussed for the three main system parameters--video frame rate, sensor control mode, and sensor field of view--as they affected the subjects' ability to perform the target search and target line-up tasks.

Video Frame Rate

The effects of video frame rate on the mean time to accomplish the two tasks are shown in Figure 32. The effect was highly statistically reliable. The probability that the differences obtained could be due to chance was much less than 0.001. For both tasks, time increased in an approximately exponential function. The differences between the 7.5 and 1.88 frames per second frame rates were small compared to the differences between the 0.47 and 0.12 frame per second frame rates. The mean search times were 57.4, 71.2, 115.5, and 154.5 seconds for the 7.5, 1.88, 0.47, and 0.12 frames per second frame rates, respectively. Although, the time differences between 7.5 and 1.88 frames per second frame rates for the two tasks were not statistically reliable, the differences may be operationally meaningful. As expected, the target search task required more time than the target line-up task. As has been demonstrated in previous studies of video frame rate, sensor control becomes more difficult as frame rate decreases, and the increased task difficulty is more pronounced with frame rates below 1 to 2 frames per second.

Figure 33 shows the effects of video frame rate on the probability of successful task accomplishment with a 93 second time limit. The relationship between frame rate and probability of successful task accomplishment is exponential, as was the case for task time. The time and probability data are largely comparable with respect to video frame rate. The difficulty of accomplishing target search with a very low frame rate is evidenced by the 0.10 probability of successful target search at the 0.12 frame per second

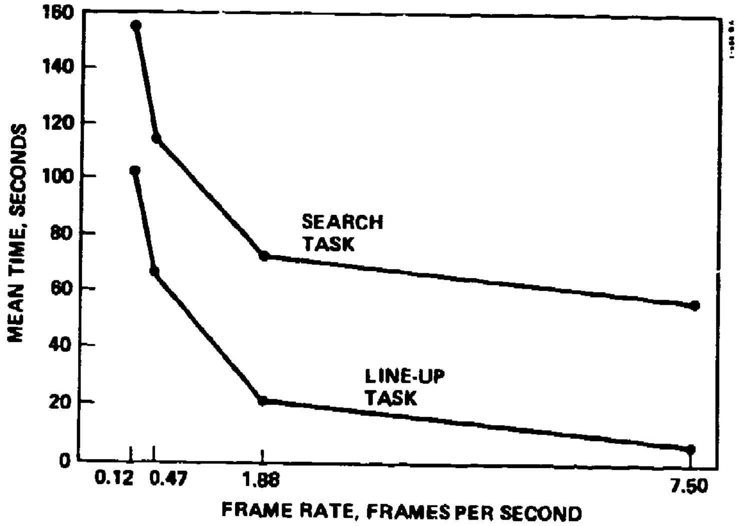

Figure 32. Effects of Video Frame Rate on Target Search and Target Line-up Task Time

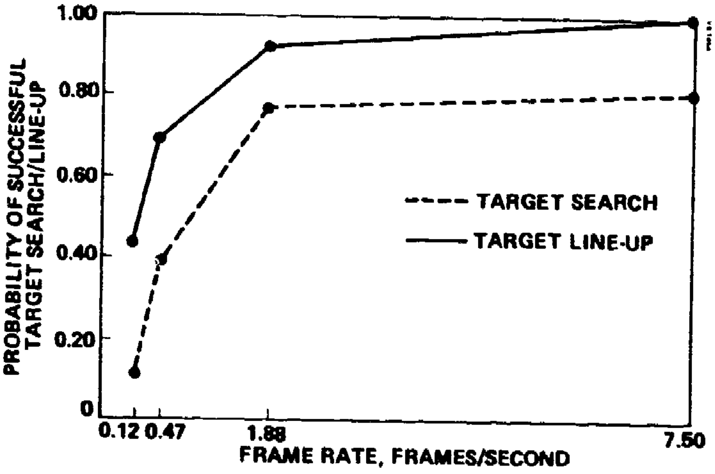

Figure 33. Effect Of Video Frame Rate On Probability Of Successful Task Accomplishment With A 93 Second Time Limit

frame rate. The difficulty of searching a large area, even when the target is easily detectable, is reflected in the 0.80 probability of successful target search at the 7.5 frames per second frame rate. In this study, the target search and target tasks were independent. Hence, the easier task of target line-up always produced better performance data than the target search task.

The results of the Cooper-Harper ratings of video frame rate are shown in Figure 34. Only the 7.5 frames per second frame rate was given a rating of 4 or less, which falls within the category of acceptable for use. These ratings reflect the subjects' overall impression of the four frame rates.

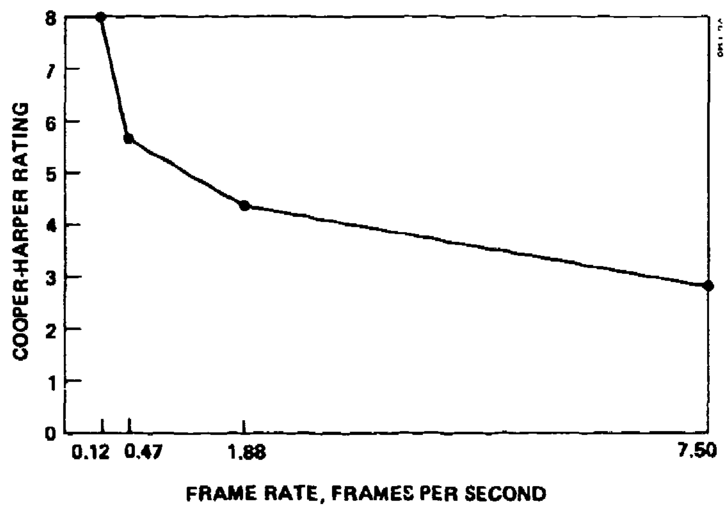

Figure 34. Cooper-Harper Ratings Of The Four Frame Rates

Sensor Control Mode

Sensor control mode did not significantly affect the subjects' time to accomplish the target search task; however, the subjects accomplished target line-up significantly faster using the image motion compensation mode than using either the continuous rate control or bang-bang control modes. The image motion compensation mode required an average of 6.7 seconds for target line-up compared to 60.3 and 78.5 seconds for the bang-bang and continuous rate control modes, respectively. These results are shown in Figure 35. The same pattern of results was obtained in the probability of successful task accomplishment data, as shown in Figure 36. The image motion compensation mode was clearly the easiest of the three modes to use and resulted in superior performance. The bang-bang mode tended to result in better target line-up performance than the continuous rate control mode, but the difference was not large enough to be statistically reliable.

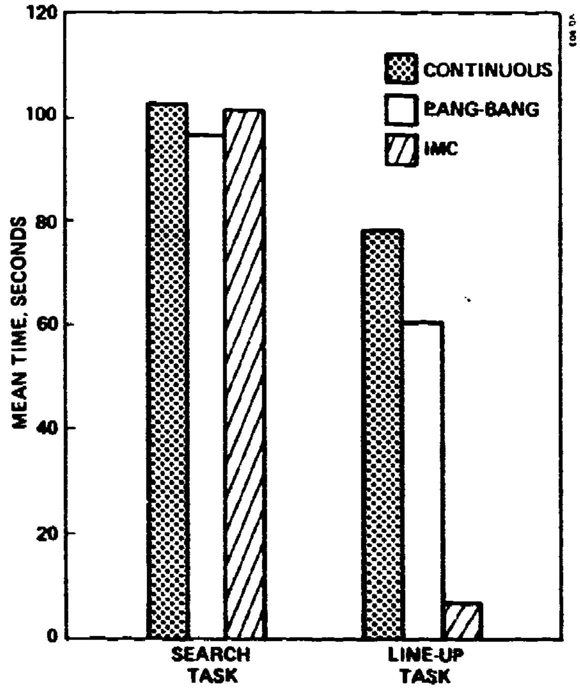

Figure 35. Effects Of Sensor Control Mode On Target Search And Target Line-up Task Time

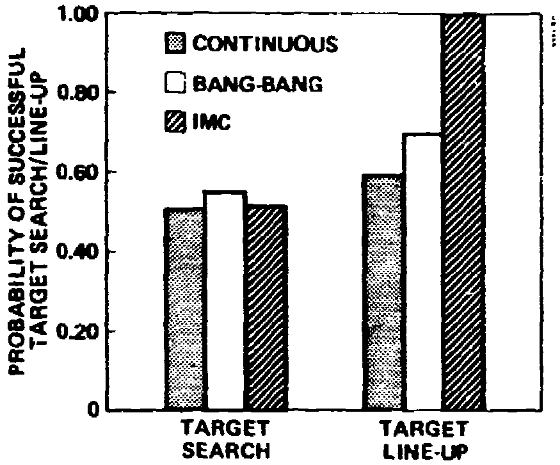

Figure 36. Effects Of Sensor Control Mode On Probability Of Successful Task Accomplishment With a 93 Second Time Limit

The Cooper-Harper ratings of the three control modes are shown in Figure 37. Only the image motion compensation mode was rated acceptable for use by the subjects. The continuous and bang-bang control modes were rated as being somewhere between undesirable and unacceptable.

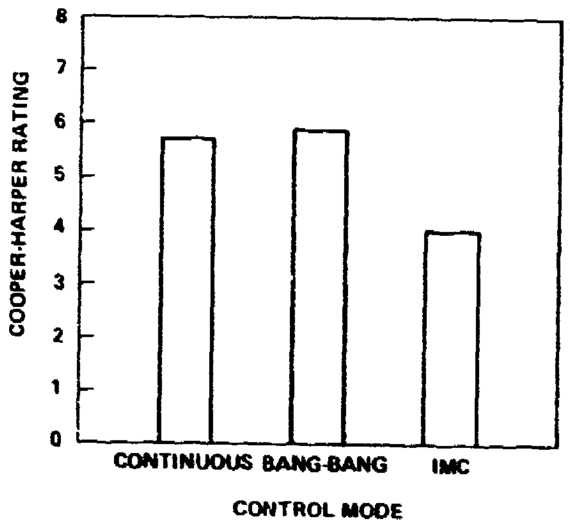

Figure 37. Cooper-Harper Ratings Of The Three Sensor Control Modes

A statistically reliable interaction ($p << 0.0001$) occurred between video frame rate and sensor control mode for the target line-up task but not for the target search task. As shown in Figure 38, sensor control mode had a relatively small affect on target search performance at all of the video frame rates. In effect, there was little advantage to using any particular one of the three control modes for coarse sensor slewing during the target search task. It is out belief that the difficulty of visually searching for a target in a large area is so great that any advantage of a particular control mode is small in comparison. Imagine looking through a rolled up magazine to search a large parking lot for your particular car.

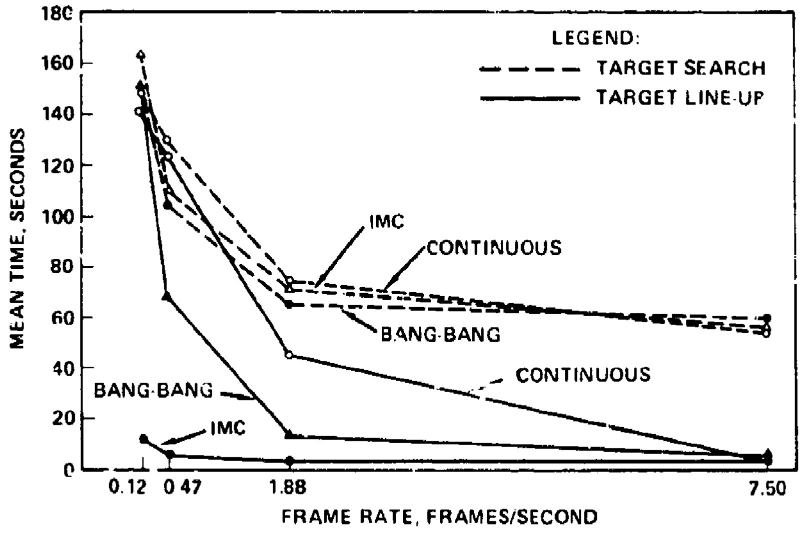

Figure 38. Interaction Between Video Frame Rate and Sensor Control Mode for Operator Task Time

The interaction between frame rate and control mode for the target line-up task, however, was statistically reliable and complex. At the 7.5 frames per second frame rate, the three control modes resulted in almost equivalent performance. Sensor slewing for target line-up was easily accomplished at the 7.5 frames per second frame rate, regardless of the control mode used. At 1.88 frames per second and less, the superiority of the image motion compensation is very evident. Except for the initial frame delay, the image motion compensation mode resulted in no performance degradation from 7.5 to 0.12 frames per second frame rates. There was a small increase in target line-up task time between the 7.5 and 1.88 frames per second frame rates for the bang-bang mode. Performance degraded rapidly at the 0.47 and 0.12 frame per second frame rates with the bang-bang mode. The continuous control mode showed considerable degradation at the 1.88 frames per second frame rate and was inferior to the bang-bang mode, except at the 7.5 frames per second frame rate, where all three control modes were equally good.

These results indicate that at a relatively high frame rate, probably between 3.75 and 7.5 frames per second, the choice of sensor slewing control modes is of little consequence. With frame rates below 2 frames per second, the image motion compensation type of control mode is clearly the best choice. A bang-bang type of control mode is superior to the continuous type of control mode, but with frame rates below about 2 frames per second, the bang-bang control mode will result in rather poor operator performance.

The probability of successful task accomplishment results for the combinations of video frame rate and sensor control mode closely parallel the task time results, as shown in Figure 39. There were relatively small differences among the three control modes at all the frame rates for the target search task. For the target line-up task, the 7.5 frames per second frame rate always resulted in successful target line-up, and successful target line-up was achieved at all four frame rates with the image motion compensation control mode. At the 1.88 frames per second frame rate, the bang-bang control mode also resulted in successful target line-up with a probability of 1.0. All other combinations of frame rates with the bang-bang and continuous control modes resulted in degraded target line-up task performance. At the 0.12 frame per second frame rate, using either the bang-bang or the continuous control modes, the subjects often lost the target (the target went out of the field of view as a result of subject overcontrol) during the target line-up task. This resulted in very low probabilities of successful task accomplishment -- 0.08 and 0.21 for the bang-bang and continuous control modes, respectively.

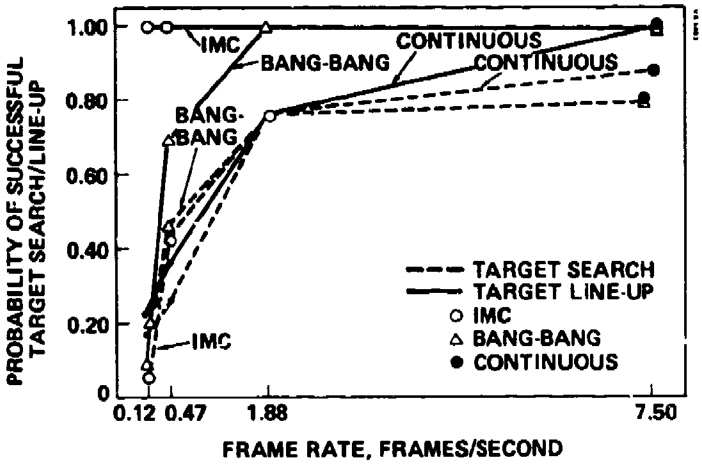

Figure 39. Interaction Between Video Frame Rate And Sensor Control Mode For Probability Of Successful Task Accomplishment With A 93-Second Time Limit

The Cooper-Harper ratings for the 12 combinations of video frame rates and sensor control modes are shown in Figure 40. All three control modes were rated acceptable at the 7.5 frames per second frame rate; however, the image motion compensation and continuous control modes were rated superior to the bang-bang control mode. The image motion compensation was rated acceptable at all but the lowest frame rate. It is interesting to note that the subjects rated the continuous mode slightly superior to the bang-bang mode, except at the lowest frame rate; the objective performance data, however, show the bang-bang mode to be superior to the continuous control mode. Apparently the subjects felt it was more difficult to use the bang-bang mode even though their performance was better than they achieved using the continuous control mode. Such results are not uncommon.

Sensor Field of View

As shown in Figure 41, increased sensor field of view resulted in better task time performance. The effect of field of view, which was statistically reliable at $p < 0.001$, was more pronounced for the target search task than for the target line-up task. Mean search times were 138.1, 91.4, and 69.5 seconds for the 5-, 10-, and 15-degree fields of view, respectively. For

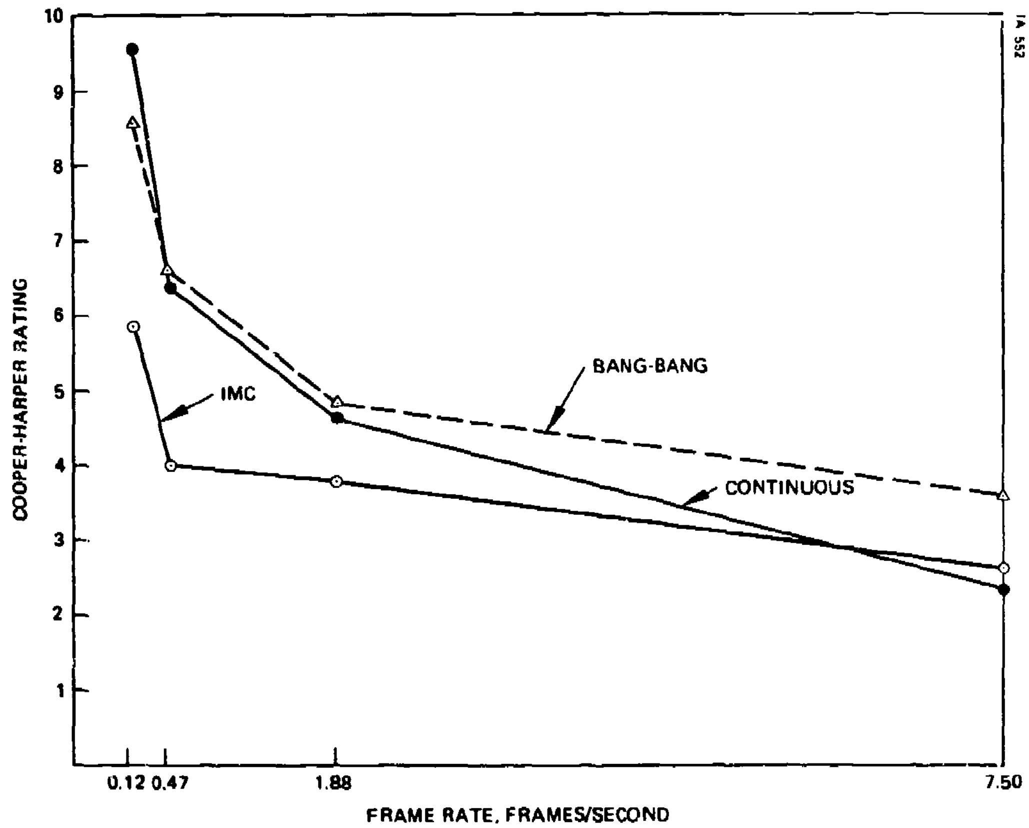

Figure 40. Cooper-Harper Ratings For 12 Combinations Of Video Frame Rates And Sensor Control Modes

the line-up task, the mean times were 57.3, 47.0, and 41.2 seconds for the 5-, 10, and 15-degree fields of view. Comparable results were obtained for probability of successful task accomplishment, as shown in Figure 42.

With an easily detectable target, it is easier to search an area with a large field of view than with a small field of view. Less sensor slewing is required, and there is simply less of a problem finding the target.

The moderate improvement of target line-up task performance with increased field of view is probably due to the reduced likelihood of losing the target with a larger field of view when the control task is difficult. The statistically reliable ($p = 0.059$) interaction between sensor field of view and video frame rate shown in Figure 43 tends to confirm this hypothesis. At the 7.5 frames per second frame rate, where the target line-up control task

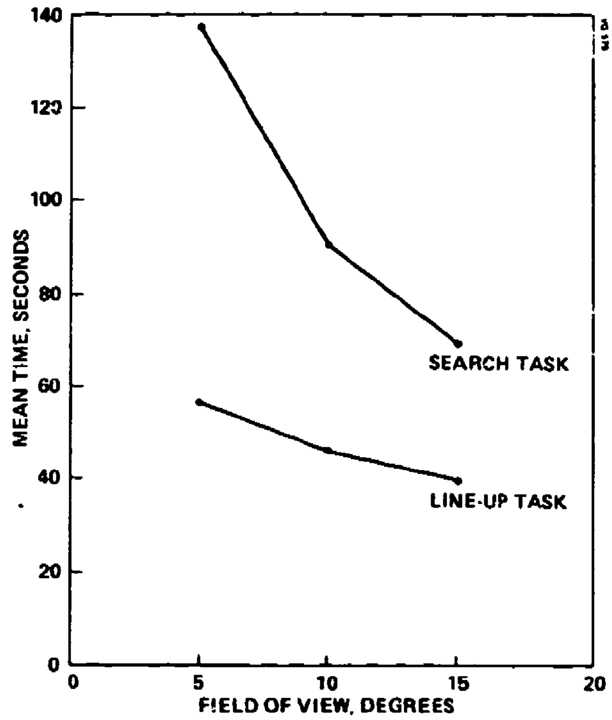

Figure 41. Effect Of Sensor Field Of View On Task Time

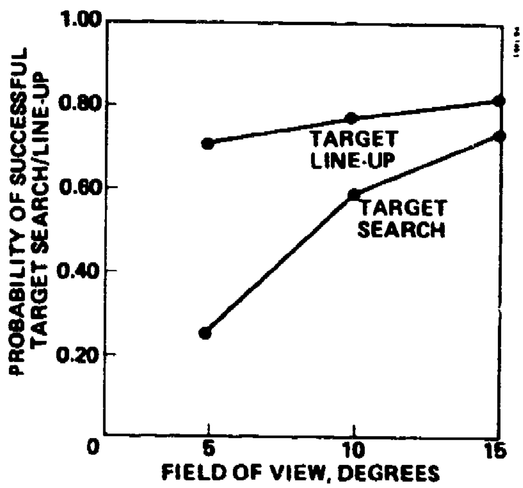

Figure 42. Effect Of Sensor Field Of View On The Probability Of Successful Task Accomplishment

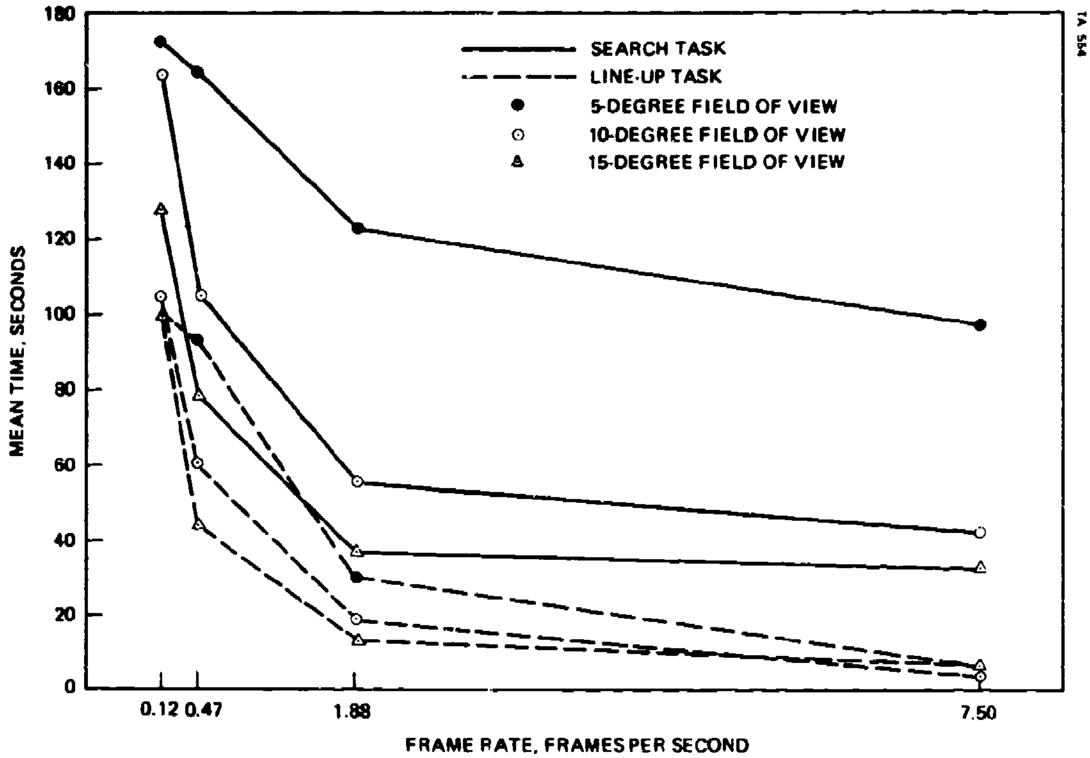

Figure 43. Interaction Between Sensor Field of View and Video Frame Rate

was easy, the three fields of view were nearly equivalent. At the 1.88 and 0.47 frames per second frame rates, performance improved with increased field of view. There were no appreciable differences among the three fields of view at the 0.12 frame per second frame rate, because the extreme difficulty of the task tends to mask any effect of field of view.

CONCLUSIONS AND RECOMMENDATIONS

Video frame rate, sensor control mode, and sensor field of view all had significant affects on the operators' ability to perform sensor slewing in the simulated search mode of a RPV system. For an operator to perform manual sensor slewing for large area target search, the video frame rate should be on the order of 2 frames per second or greater. The choice of a particular control mode will have little affect on the operator's large area sensor slewing performance as long as the particular control mode selected is reasonably well designed. Large fields of view are advantageous for large area sensor slewing; however, the effects of field of view on target detectability must also be considered when selecting the field of view for the RPV search mode. The relationship between sensor field of view and target detection performance is typically an inverse function.

Once the target has been detected during the large area search process, the sensor must be slewed such that the target is near the center of the field of view and a narrow field of view for target recognition and/or target tracking can be selected. Video frame rate and sensor control mode both determine the operators' ability to perform this task. With an image motion compensation type of control mode, frame rates as low as 0.12 frame per second can be used with only a small increase in operator task time. With a bang-bang type of control mode, frame rates as low as 2 frames per second can be used and still achieve a high level of operator performance. With a conventional rate control syste, only the highest frame rate used in this study (7.5 frames per second) resulted in acceptable performance. Field of view is not an important determiner of the operators' ability to slew the sensor to get the target near the center of the field of view, except when the frame rate-control mode combination results in a difficult control task and the operator allows the target to get out of the sensor field of view.

The findings of this study indicate a 15:1 bandwidth reduction (compared to a 30 frames per second frame rate) can be achieved by using a 1.88 frames per second frame rate during the manual sensor slewing target search process. Once the target is found, a 256:1 bandwidth reduction is attainable if an image motion compensation type of control system is used to slew the sensor for target line-up.

SECTION 4

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APPENDIX A

SUMMARY TABLES FOR ANALYSES OF VARIANCE

TABLE A-1. ANALYSIS OF VARIANCE FOR VARIABLE COVERAGE STUDY: TARGET DETECTION

SOURCE OF VARIANCE	DEGREES OF FREEDOM	SUMS OF SQUARES	F-RATIO	PROBABILITY
Bandwidth Compression (BC)	4	1726.87	4.83	0.0016
Target Numerosity (TN)	1	2325.67	26.04	0.0001
Atmospheric Attenuation (AA)	2	28.33	0.16	0.85
Global Complexity (GC)	2	30.54	0.17	0.85
Target Type (TT)	4	416.24	0.98	0.42
Target Aspect (TA)	1	929.99	9.96	0.0019
BC X TN	4	1655.81	4.63	0.002
BC X AA	8	509.29	0.71	0.68
BC X GC	8	396.78	0.54	0.82
AA X TN	2	52.33	0.29	0.75
TN X GC	2	17.84	0.10	0.91
TN X TT	4	436.25	1.03	0.40
TN X TA	1	869.19	9.31	0.0027
BC X TN X AA	8	531.03	0.74	0.65
BC X TN X GC	8	349.12	0.47	0.87

TABLE A-2. ANALYSIS OF VARIANCE FOR VARIABLE COVERAGE STUDY: TARGET RECOGNITION

SOURCE OF VARIANCE	DEGREES OF FREEDOM	SUMS OF SQUARES	F-RATIO	PROBABILITY
Bandwidth Compression (BC)	4	4632.03	6.98	0.0001
Target Numerosity (TN)	1	5721.44	34.47	0.0001
Atmospheric Attenuation (AA)	2	315.93	0.95	0.39
Global Complexity (GC)	2	123.33	0.36	0.70
Target Type (TT)	4	733.09	0.99	0.41
Target Aspect (TA)	1	2588.06	15.82	0.0001
BC X TN	4	1597.95	2.41	0.057
BC X AA	8	1899.97	1.43	0.20
BC X GC	8	1745.03	1.29	0.26
AA X TN	2	438.97	1.32	0.27
TN X GC	2	27.74	0.08	0.92
TN X TT	4	1262.42	1.71	0.15
TN X TA	1	1734.63	10.60	0.0014
BC X TN X AA	8	737.77	0.56	0.81
BC X TN X GC	8	907.24	0.67	0.78

TABLE A-3. ANALYSIS OF VARIANCE FOR FIXED COVERAGE STUDY: TARGET RECOGNITION

SOURCE OF VARIANCE	DEGREES OF FREEDOM	SUMS OF SQUARES	F-RATIO	PROBABILITY
Bandwidth Compression (BC)	4	2633.21	3.79	<0.01
Atmospheric Attenuation (AA)	2	287.39	0.83	>0.25
Target Type (TT)	4	2459.98	3.21	0.026
Target Aspect	1	619.87	3.44	0.067
BC X AA	8	1471.49	1.06	>0.25
TT X TA	4	970.74	1.27	0.305

TABLE A-4. ANALYSIS OF VARIANCE FOR SENSOR SLEWING STUDY: TASK TIME

SOURCE OF VARIANCE	DEGREES OF FREEDOM	SUMS OF SQUARES	F-RATIO	PROBABILITY
Control Mode (CM)	2	166520	45.60	1.70×10^{-18}
Frame Rate (FR)	3	1039324	168.50	3.51×10^{-6}
Field of View (FOV)	2	223417	54.33	1.43×10^{-4}
Task (T)	1	471103	229.14	5.24×10^{-6}
Replication (R)	1	37.18	0.018	0.898
CM X FR	6	138898	12.68	4.57×10^{-13}
CM X FOV	4	6111	0.837	0.502
CM X T	2	170747	46.76	6.69×10^{-19}
CM X R	2	6976	1.91	0.149
FR X FOV	6	48917	3.97	0.059
FR X T	3	276.06	0.045	0.986
FR X R	3	12740	2.07	0.206
FOV X T	2	86552	21.05	0.0019
FOV X R	2	1203.1	0.293	0.756
T X R	1	6180.5	3.01	0.133
CM X FR X FOV	12	24229	1.11	0.350
CM X FR X T	6	144008	13.15	1.50×10^{-13}
CM X FR X R	6	8852.4	0.808	0.564
FR X FOV X T	6	12308	1.00	0.50
FR X FOV X R	6	24800	2.01	0.208
FOV X T X R	2	1370.8	0.333	0.729
CM X FOV X R	4	2687.9	0.368	0.831
CM X FOV X T	4	10536	1.44	0.220
CM X R X T	2	14266	3.91	0.021
FR X R X T	3	9716.0	1.58	0.290
CM X FR X FOV X T	12	34709	1.58	0.095
CM X FR X FOV X R	12	22727	1.04	0.411
CM X FR X T X R	6	14547	1.33	0.243
CM X FOV X T X R	4	4099.1	0.561	0.691
CM X FR X FOV X T X R	12	12963	0.592	0.849